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Title page

Limits to Growth Redux: A system dynamics model for assessing energy and climate change constraints to global growth

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Abstract

This study investigates the notion of limits to socioeconomic growth with a specific focus on the role of climate change and the declining quality of fossil fuel reserves. A new system dynamics model has been created. The World Energy Model (WEM) is based on the World3 model (*The Limits to Growth*, Meadows et al., 2004) with climate change and energy production replacing generic pollution and resources factors. WEM also tracks global population, food production and industrial output out to the year 2100. This paper presents a series of WEM's projections; each of which represent broad sweeps of what the future may bring. All scenarios project that global industrial output will continue growing until 2100. Scenarios based on current energy trends lead to a 50% increase in the average cost of energy production and 2.4-2.7°C of global warming by 2100. WEM projects that limiting global warming to 2°C will reduce the industrial output growth rate by 0.1-0.2%. However, WEM also plots industrial decline by 2150 for cases of uncontrolled climate change or increased population growth. The general behaviour of WEM is far more stable than World3 but its results still support the call for a managed decline in society's ecological footprint.

Keywords - limits, growth, climate change, energy, population, system dynamics

1 Introduction

The notion of limits to growth is based on the premise that exponential growth of human population and physical output cannot continue forever on a finite planet (Lovejoy 1996). Such concerns have been raised for centuries and were further popularised by the Limits to Growth (LTG) research; the original LTG publication (Meadows et al. 1972) sold over 12 million copies and has been described as the founding text of the modern environmental movement (Jackson & Webster 2016).

The LTG approach is distinguished by its use of a global system dynamics model called World3 to create projections of the future. World3 projected that, having overshot the Earth's carrying capacity, humanity was left facing two futures - involuntary collapse driven by physical limits or a controlled reduction of the ecological footprint by deliberate social choice.

In response to growing environmental and energy concerns, the UK government recently launched a parliamentary group on LTG to "*create the space for cross-party dialogue on environmental and social limits to growth*" (Jackson & Webster 2016). The LTG argument remains relevant but few researchers have taken up the mantle laid down by the LTG team to improve the underpinning World3 model.

This paper presents a new system dynamics model, entitled the World Energy Model (WEM), to investigate how climate change and the declining quality of fossil fuel reserves will affect socioeconomic growth in the 21st century. The study compares the projections of WEM to the World3 model, investigates the impact of climate change policies on the state of the world and considers the likelihood of industrial decline. The results support broad policy themes and will hopefully stimulate further attempts to improve the process of model making.

2 Background

2.1 Limits to Growth Summary

The LTG research is documented in three publications for the general public (Meadows et al. 1972; Meadows et al. 1992; Meadows et al. 2004) and one detailed technical report (Meadows et al. 1973). The LTG researchers believe that three features of the world system make it unstable and prone to future collapse; exponential growth in human activity, limits in the Earth's system and delays in societies reaction. These features were built into a global system dynamics model called World3.

World3 projects the flow of five key variables to the year 2100; human population, industrial capital, non-renewable resources, agriculture, and pollution. Global averages are used for all parameters and complex measures such as pollutants and non-renewable resources aggregated to a single value. Figure 1 presents a simplified diagram of the model. The numerous nonlinear relationships and feedback structure make the whole model dynamically complex.

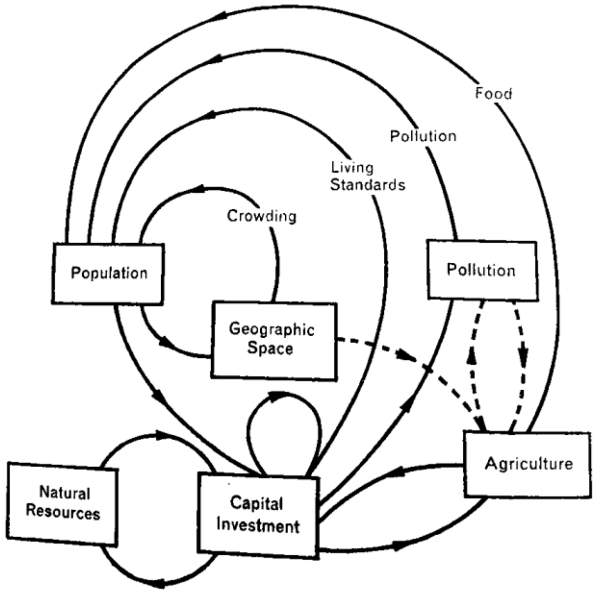

Figure 1; World3's Main Feedback Loops - The boxes represent the main subsystems and the arrows show the causal links (Cole et al. 1973)

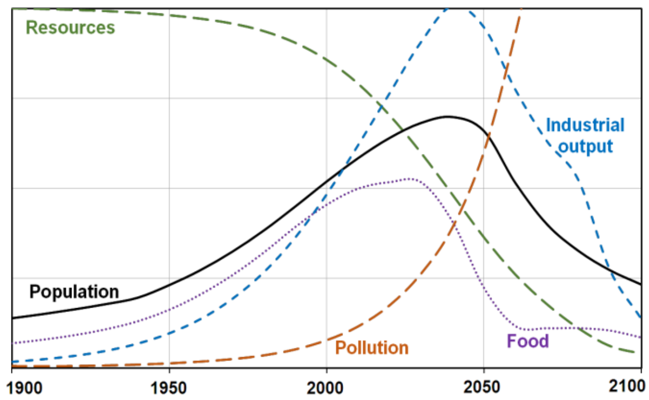

Figure 2; World3-03 Scenario 2 – Global industrial collapse is projected due to increasing pollution costs (Meadows et al. 2004)

LTG did not make an explicit prediction about the future state of the world but instead presented a series of World3's scenarios, each based on varying social and environmental assumptions. The majority of these scenarios projected global industrial output to peak within the 21st century. Industrial decline occurs because increasing capital is drained into either extracting resources, adapting to pollution, producing sufficient food or developing technologies to offset these physical limits. The post peak trajectories are described as highly speculative due to the unpredictable response to industrial decline. Figure 2 presents a typical scenario, where pollution grows exponentially and drives industrial collapse.

World3 only projects a sustainable future when a deliberate constraint is placed upon population and material growth. LTG argued that society should target a form of equilibrium state, where material consumption no longer grows. The LTG researchers also hoped that their work would lead to a new movement of justifying views with explicit and examinable computer models. World3 was "both a demonstration of what can be done and a challenge to do it better" (Meadows et al. 1973).

2.2 System Dynamics

World3 remains the most well known example of system dynamics modelling; using stocks, flows, internal feedback loops and time delays to investigate complex and non-linear behaviour.

The basis of system dynamics is recognition that the behaviour of a system is dependent on the system structure as much as the individual components. Whilst most scientists study the world by breaking it up into smaller and smaller pieces, system dynamics encourages a whole and continuous view; striving to look beyond events to see the dynamic patterns underlying them (MIT 1997). Many global forecasts are inconsistent, one part of the forecast contradicts another, because they fail to consider these underlying relationships (Randers 2012).

2.3 The LTG Argument Today

The LTG research raised environmental awareness but ultimately failed to lead to the political actions called for. Critiques of World3 tended to focus on the level of aggregation and political bias within the model. Continued socioeconomic growth over the last 45 years has led to calls to relegate the work to the "dustbin of history" (Lomborg & Rubin 2002). Many critics either misinterpret the LTG message or perpetuate the myth that LTG was flawed because it had forecast collapse to have occurred by the end of the 20th century (Turner 2012).

An assessment of events over the last 40 years actually shows that major variables such as population, industrial output and food production are closely following the LTG ‘business as usual’ scenario (Turner 2012). In order to assess the likelihood of the world further following World3’s scenario into industrial decline, it is important to consider the state of the underlying physical constraints.

Food and general resource scarcity appear no closer to materialising into significant constraints to industrial growth than 45 years ago. Food production per capita has steadily increased and that trend is expected to continue to 2050 (Alexandratos & Bruinsma 2012). The cost of raw materials has remained relatively constant with continued technological advances offsetting the diminishing quality of reserves (Yamada & Yoon 2014; Eastin et al. 2011).

The depletion of fossil fuel reserves is arguably the most significant example of resource scarcity in the modern world. Oil and gas reserves are falling in quality rather than quantity, as demonstrated by the shifts to first offshore and now unconventional resources. Despite technological advances, real oil prices are approximately three times higher than the average price through the mid-20th century (BP 2016). Increasing energy costs could drain industrial capital in the same manner that LTG hypothesised the increasing cost of resource extraction would.

Meanwhile, environmental issues have turned out *"considerably worse than the Club of Rome's projections"* with concerns that climate change, biodiversity loss, damage to nitrogen cycles and land use could all threaten the maintenance of the Earth system (Jackson & Webster 2016). Policy attention and social discourse have increasingly shifted emphasis from general growth concerns to climate change (Eastin et al. 2011). Climate change and the depletion of fossil fuel reserves appear to be the most threatening examples of physical constraints in the modern world and are the main focus of this paper.

3 Methodology

The World Energy Model (WEM) is a systems dynamics model, written in STELLA, and based on the World3-03 model (private communication from Jorgen Randers, 2016) that was created for the latest LTG publication (Meadows et al. 2004). The core change from World3-03 to WEM is the replacement of generalised resource and pollution terms with specific energy and climate change factors. WEM's five main variables are human population, industrial capital, food production, energy production and global warming.

WEM recreates historical data from 1900 to 2016 and projects future scenarios out to 2100. There is clearly huge uncertainty in producing such a long-range forecast. Like World3 before it, the purpose of this model is not to predict specific values but to produce "*broad sweeps of the future*" (Meadows et al. 2004). The level of detail in the model is only valid for defining general behaviour modes and trends.

Three main scenarios were defined to highlight the effect of GHG emission mitigation policies on energy use and the future state of the world:

- **Scenario 1 - No pollution control**
- **Scenario 2 - Current trends** - follows the IEA's New policies scenario (current and expected future policies) to 2040 and extrapolates these energy trends to 2100 (IEA 2016b).
- **Scenario 3 - 2°C global warming target**

3.1 World3 to WEM

The original resource and pollution sub-models were completely removed from the model. Details of the replacement sub-models and justifications for their key inputs are detailed in the following sections. Only two changes have been made to the remaining population, capital and agricultural subsectors:

- Desired family size has been made less responsive to high levels of industrial output per capita (baseline population projections remain low, equivalent to UN's 20th percentile growth (UN 2017)).
- The relationship between agricultural inputs and yields has been extrapolated to prevent yields hitting a fixed limit.

3.2 Building Energy into WEM

This analysis hypothesises that increasing cost of energy, rather than resource extraction, could drain industrial capital and therefore constrain industrial growth. No projections of global energy cost beyond the year 2050 could be found within the literature. The Future of Energy Model (FEM) was therefore created to project the average cost and GHG emissions intensity of energy to the year 2100.

3.2.1 FEM Overview

FEM is a Microsoft Excel model that projects the global energy mix (the percentage of each energy source in the Total Primary Energy Demand (TPED)) up to 2100 based on the cost projections and pollution factors of each major energy source. From this energy mix, the average cost of energy production can be estimated. FEM separates energy production into:

- a transport sector, which currently accounts for 27% of TPED (IEA 2016a);
- a combined heating and electricity sector.

3.2.2 Heat and Electricity Sub-model

The following energy source cost assumptions were made:

- Energy source costs are proportional to broad long-term price trends, a relationship that is strongly debated within the literature (Henckens et al. 2016; Bouleau 2012).
- Fuel costs follow trends over time but are independent of total production.
- The costs of renewables and nuclear power have been converted to an equivalent fuel cost ($/mtoe) by comparison against the levelised cost of electricity for fossil fuel sources.

Figure 3 to Figure 6 present the inflation adjusted cost of each energy source; coal, oil, gas, renewable technologies, biomass and nuclear power. The only future technology included is Carbon Capture and Storage (CCS). CCS with gas or coal power are introduced as alternative energy sources from 2020. The model assumes that CCS increases the fuel cost by 30%; a low estimate of current average costs has been taken to balance future technology improvements (Rubin 2015).

An additional *demand cost factor* has been applied to renewable sources and nuclear power. *Demand cost factors* are proportional to the sources share in the energy mix and were calculated based on optimising FEM's production to historic data (1900-2015) and IEA forecasts (2015-2040) (IEA 2016b). When production is 25% of the heating and electricity sector, costs are increased by 100% for renewables and by 50% for nuclear power. The *demand cost factor* represents:

1. Increased demand management costs - renewables are generally intermittent and nuclear power cannot be ramped up/down to meet demand
2. Increased cost of using renewables and nuclear power for heat rather than electrical production - electricity currently accounts for only 30% of the electricity and heating sector. Electrification of heating sectors is not always feasible (Eyre 2011) and renewable sources are generally less economically competitive in heat production compared to electricity production (Chaudry et al. 2015).

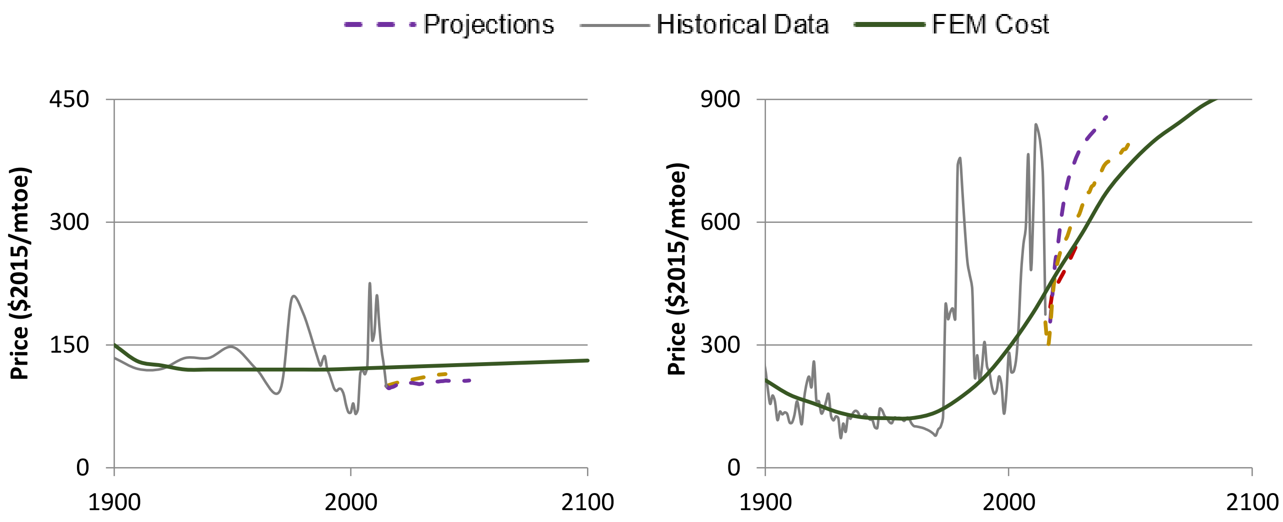

Figure 3; Coal Prices - Approximate historical data from 1900 (McNerney et al. 2011)*, detailed from 1987* (BP 2016) *and projections to 2050* (IEA 2016b; EIA 2017)

Figure 4; Oil Prices - Historical data from 1860 (BP 2016) *and projections to 2050* (The World Bank 2017; IEA 2016b; EIA 2017)

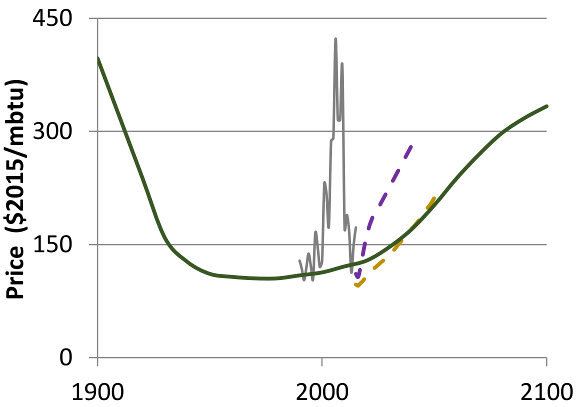

Figure 5; Natural Gas Prices - Historical data from 1989 (BP 2016) *and projections to 2050* (EIA 2017; IEA 2016b)

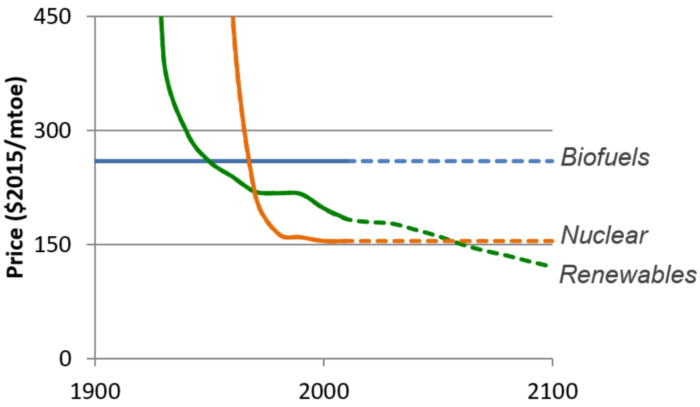

Figure 6; Biofuel, Renewable and Nuclear Prices - Estimates from secondary data and exclude demand cost factors for nuclear & renewables

Pollution factors model the global effort to move to cleaner energy sources. Pollution costs, presented in Table 1, are proportional to the GHG intensity of each source but with an increased value for coal and nuclear power due to air pollution and radioactive waste concerns respectively. This increase was based on optimising the model's projections against historical and projected production data (from 1900 to 2040). CCS, incorporated from 2020 onwards, reduces the GHG emissions of coal and oil by 85% (Leung et al. 2014).

Table 1; Pollution Factors - Energy source pollution factors are based on GHG emissions intensities from averaged datasets (EPA 2014; UK Gov 2016; IPCC 2014)

	Biofuel	Coal	Coal +CCS	Oil	Gas	Gas + CCS	Nuclear	Renewables
GHG emissions (Coal=100)	27	100	15	79	57	9	1	3
Pollution Costs factor	27	120	35	79	57	9	100	3

The algorithm to convert energy costs into a production mix is shown below for the electricity and heating sector. The following factors were calculated by optimising the model's production mix against historical data and IEA projections between 1900 and 2040:

- Pollution multiplier - defines the impact that pollution costs have on energy production. It represents the conscious effort to decarbonise energy production and so changes over time and by scenario.
- Power function (optimised value = 3) - defines the value of diversity in the energy mix
- Weighting function (optimised value = 0.15) - represents the time delay for energy production to shift to cheaper sources.

For a total of *n* energy sources (i) and for each decade (j):

$$TotalCost_i^j = FinancialCost_i^j + \left(PollutionCost_i^j \times PollutionMultiplier^j\right) \quad \text{(Eq. 1)}$$

$$Score_i^j = \left(\frac{TotalCost_i^j}{\sum_{i=1}^{n} TotalCost_i^j / n}\right)^{3} \quad \text{(Eq. 2)}$$

$$IdealProduction_i^j = \frac{Score_i^j}{\sum_{i=1}^{n} Score_i^j} \quad \text{(Eq. 3)}$$

$$Production_i^j = IdealProduction_i^j \times \mathbf{0.15} + Production_i^{j-1} \times (1 - \mathbf{0.15}) \quad \text{(Eq. 4)}$$

3.2.3 Transport Sub-model

The transport sub-model is very similar with a financial and pollution cost defining an ideal production mix. However, it is difficult to compare transport fuel costs without breaking down into further sectors. Costs were therefore assumed to be proportional to energy source costs and optimised to generate results that matched historic data and future projections. Figure 7 and Figure 8 compare the FEM transport production mix to the target data.

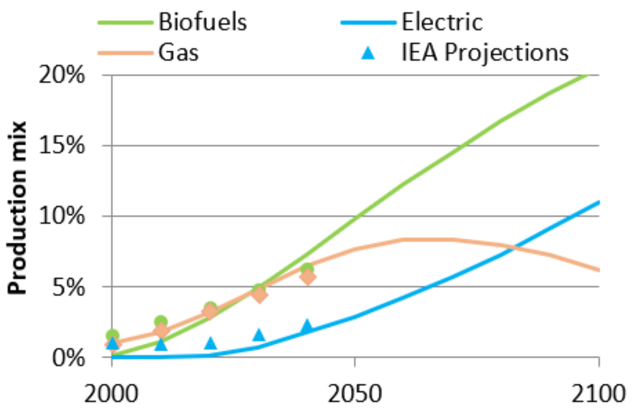

Figure 7; Alternative Fuels Transport Production Mix- FEM projections against target IEA projections

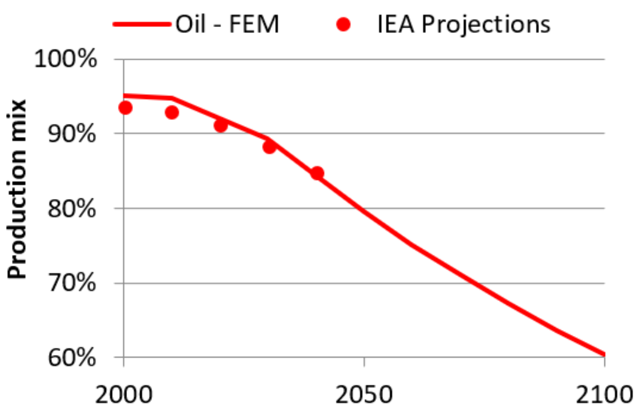

Figure 8; Oil Transport Production - FEM projections against target IEA projections

3.2.4 FEM Results

The energy production mix closely follows historical data and for Scenario 2 (current trends), is consistent with the IEA's projection out to 2040 (IEA 2016b). By 2100, fossil fuel production without CCS is reduced from 82% of TPED today to 60%, 42% and 25% of TPED for Scenarios 1, 2 and 3 respectively.

Figure 9 and Figure 10 present the key outputs of FEM; the projected cost and GHG emissions intensity of energy. Energy costs approximately double through the 21st century, this increase is predominantly driven by the rising cost of oil. Transport costs fail to significantly decouple from oil costs because there is a lack of substitutes of the necessary quality and quantity (Hall et al. 2013). Diversifying the transport fuel industry could reduce the potential for such dramatic oil shocks. Gas costs also rise substantially but the electricity and heating sectors are more diverse and therefore more resilient.

As expected, increasing efforts to reduced GHG emissions increases energy costs. Between 2020 and 2100, Scenario 2 (current trends) is 4% more expensive than scenario 1 (no pollution control) but cumulative emissions decrease by 18%.

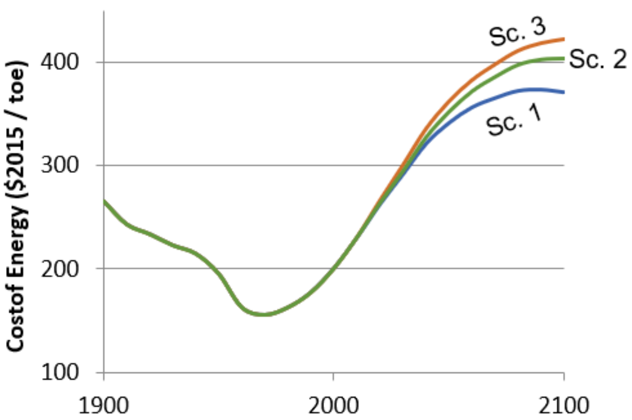

Figure 9; FEM Energy Cost Projections

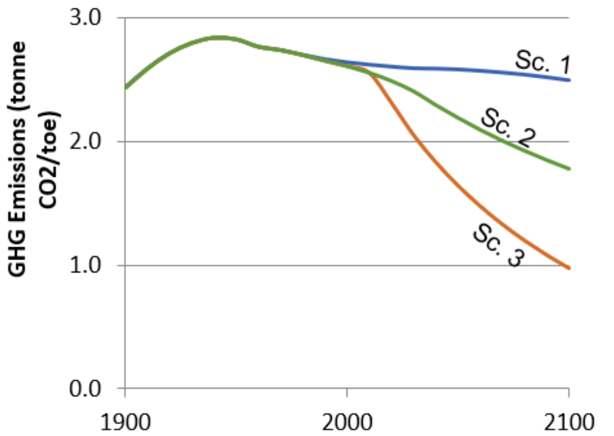

Figure 10; FEM GHG Emission Intensity Projections

3.2.5 Energy costs in WEM

FEM's results support the initial hypothesis that energy costs are increasing and represent a potential constraint to future socioeconomic growth. The key cost and emission intensity results are built into the world systems model and given in detail in Appendix A.

WEM replaces the Fraction of Capital Allocated to Obtaining Resources (FCAOR) used in World3 with the Fraction of Capital Allocated to Generating Energy (FCAGE). The theory of resource extraction acting as a drain on industrial capital is equally applicable to energy production (Hall & Klitgaard 2012). Economic fluctuations can often be explained by variations in a society's access to cheap and abundant energy (Hall et al. 2013). Lambert suggests that in the US, recessions follow whenever energy expenditure rises above 10% of GDP (Lambert et al. 2013). Contrastingly, the recent fall in energy costs, driven by the shale gas boom, has led to a surge in the country's economic growth rates (Brown & Yucel 2013).

The FCAGE is assumed to be proportional to the average cost of energy (as calculated in FEM) on the basis that financial costs tend to follow capital. King estimates that from 1978 to 2010, energy expenditure fluctuated between 3% and 10% of gross world product (King et al. 2015). In this analysis, the FCAGE has been set to average 5% through the 20th century, the same magnitude as the FCAOR, to give consistent growth projections with World3.

3.3 Building Climate Change into WEM

Figure 11 presents the climate change sub-model of WEM. The model calculates the energy intensity of industrial output, Total Primary Energy Demand (TPED), annual GHG emissions, global warming, and finally the end-point impacts of climate change. Justification for the calculation of these variables is given in the following section. The sub-model takes one input from the main model (industrial output) and gives three key outputs:

- FIOA (Fraction of Industrial Output Allocated to) Efficiency - annual investment in energy efficiency, interface with main model as a drain on total industrial output
- Flood Cost - the cost of increased flood risks, interface as a drain on total industrial output
- Land Yield Degradation - interface via a percentage reduction of agricultural yields

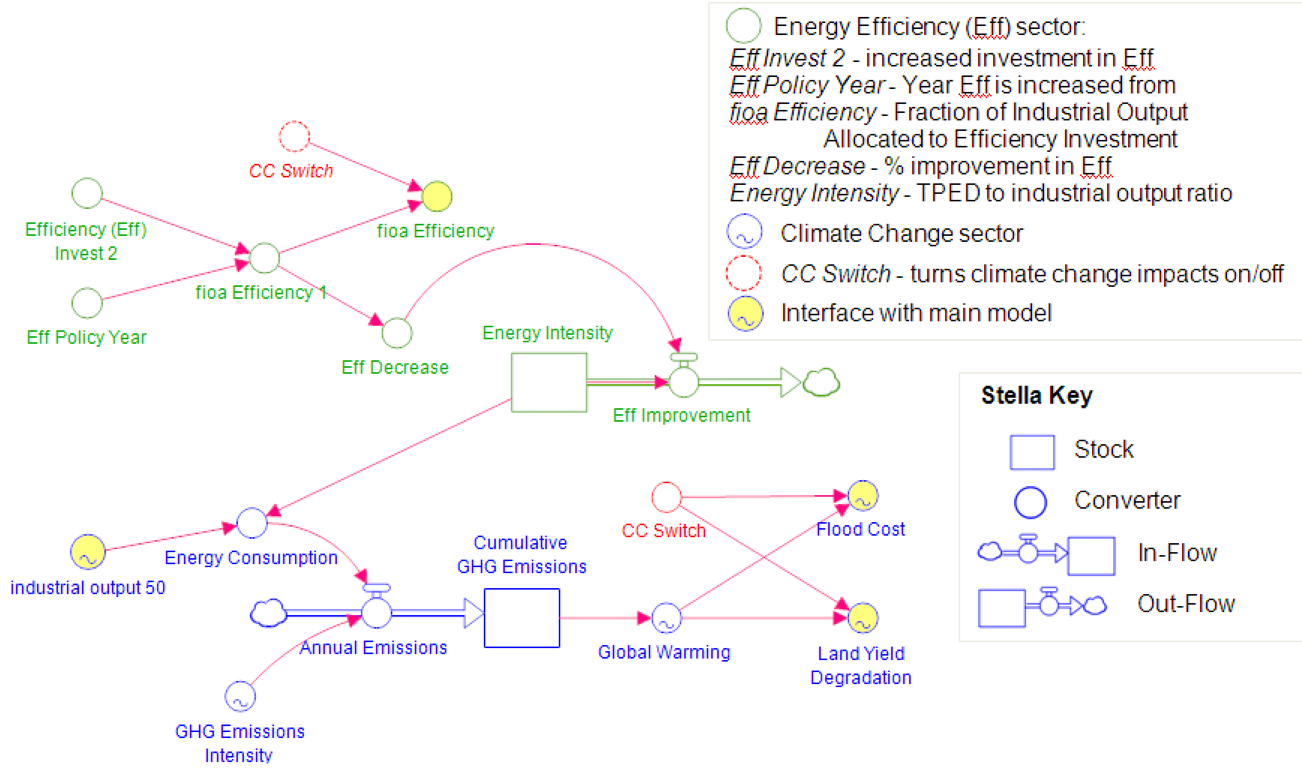

Figure 11; WEM Climate Change Sub-model – System dynamics model to calculate the end-point impacts of climate change

3.3.1 Energy Intensity

Energy intensity is measured as the ratio between TPED and industrial output. The continued decline in energy intensity is critical to limiting global warming. Changes to the energy intensity in WEM are based on data analysis from the IEA's scenario projections (IEA 2016b) and the following logic:

- The IEA's scenario analysis provides an energy efficiency investment for each scenario. The majority of this investment is in the transport sector. However, the additional cost of alternative transport options is already accounted for in WEM’s energy cost (see Section 3.2.3).
- An optimistic assumption was therefore made to only consider the efficiency investment in buildings and appliances - quoted as 25% of the total investment (IEA 2016b).
- Figure 12 summarises the relationship between this efficiency cost and the annual change in energy intensity for each scenario. The assumed relationship underestimates the efficiency cost required and is only valid when used in conjunction with the appropriate increase in transport costs for each scenario.
- The scenarios in this analysis must not use a high investment in energy efficiency without also implementing aggressive (and therefore expensive) changes to the transport sector.

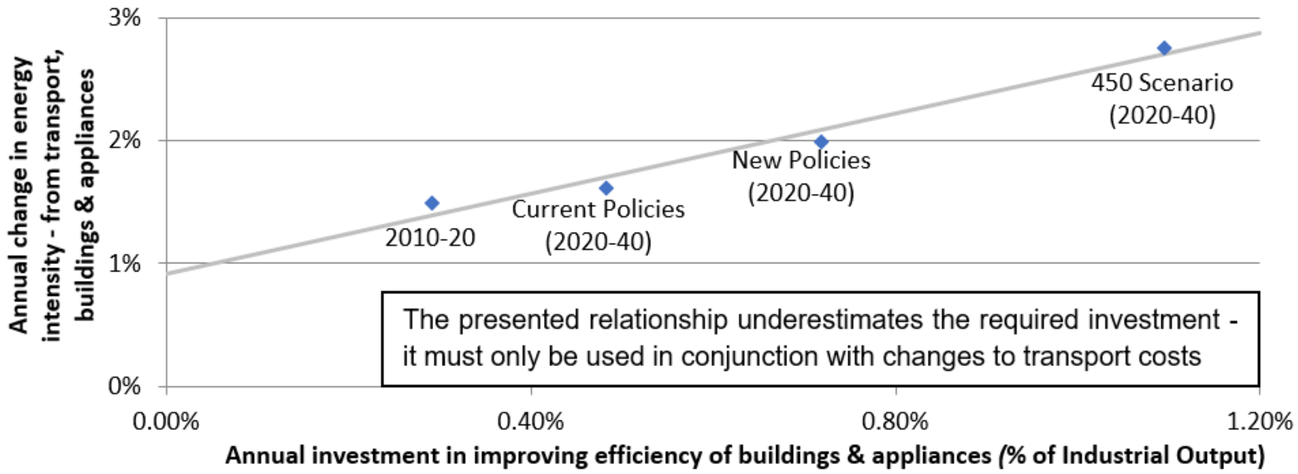

Figure 12; WEM Energy Intensity - Reduction of energy intensity proportional to the efficiency investment - data points based on IEA scenario analysis (IEA 2016b)

3.3.2 Climate Change

GHG emissions are a product of industrial output, the energy intensity of the economy and the GHG intensity of the energy sector (from FEM). Cumulative GHG emissions are converted to a global increase in temperature based on Figure SPM.10 of the IPCC report (IPCC 2013). The climate's ability to assimilate GHG emissions has been subsumed in this relationship.

3.3.3 Impacts

The aggregated nature of the model makes it difficult to convey the true level of damage caused by climate change. Climate change will affect some people and some countries far more drastically than others. Impacts will generally be greater in developing countries, where climates are typically warmer, and this disparity will lead to global social issues, such as mass migration, not considered within WEM.

On this globally aggregated scale, the effect of climate change on work productivity, agricultural yields and flood damages were considered significant to the future of the global socioeconomic system. Biodiversity loss has a limited direct effect on global output and the increase in heat-wave deaths was considered inconsequential when factoring in the decline in winter mortality rates.

Labour Productivity

Labour productivity is affected by temperature and the subsequent economic impact is dependent on the availability of labour. Many climate change reports do not mention labour productivity and yet others quote potential losses of $500-2500 billion/year by 2030 (Kjellstrom 2015; DARA 2010).

World3 assumes that an excess of labour is maintained and so industrial output is a function of industrial capital. The LTG authors argued that "*economic development was never significantly constrained by a global shortage of labour*" (Meadows et al. 1972). WEM maintains this assumption and so the impact of labour productivity changes has not been included.

Agricultural Yields

Climate plays a central role in crop growth and consequently, climate change threatens global agricultural production and food security. Figure 13 shows considerable variation in estimates of global warming's impact on crop yields. WEM takes an average of estimates both with and without carbon dioxide fertilisation because of the uncertainty surrounding its effects. Furthermore, many yield studies do not consider the full impacts of climate changes with factors such as more extreme weather patterns or the increased pest risk ignored (Soussana et al. 2010). The rate of degradation increases with greater global warming because plant growth is a highly non-linear function of heat.

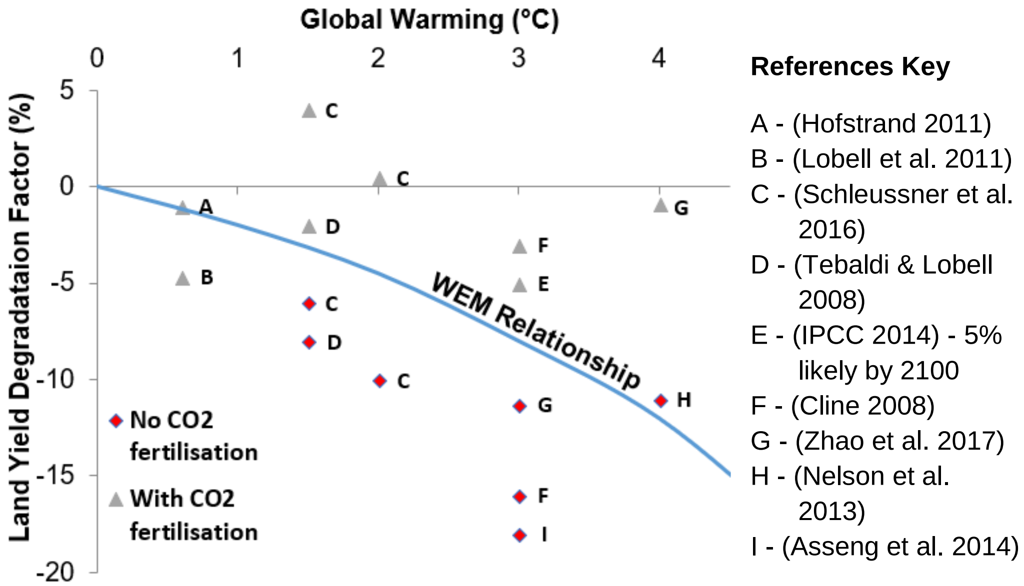

Figure 13; Agricultural Yield Degradation - The assumed relationship between global warming and globally aggregated crop yields takes account of estimates both with and without carbon dioxide fertilisation

Flood Damage

Over 5% of the global population live less than 5 metres above sea level and are increasingly vulnerable to flooding, storm surges and cyclones as sea levels rise (Kummu et al. 2016). Figure 14 presents the assumed relationship between global warming and the cost of flood damage within this century. This does not represent the full potential of flood damage; even if GHG concentrations were stabilised today, sea levels would continue rising for centuries to come (Solomon et al. 2009). Damages again increase disproportionately; rising water only causes significant damage once it overshoots the land or coastal defence protecting assets (Boettle et al. 2016).

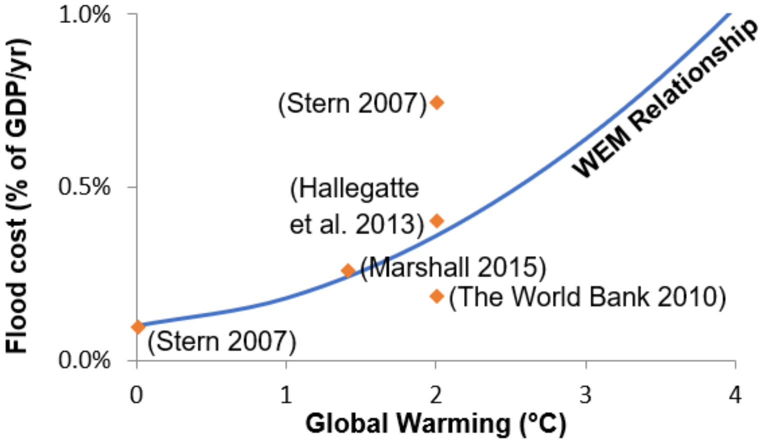

Figure 14; Flood Costs - Global warming drives a non-linear increase in 21st century flood damage costs

4 Results & Discussion

This paper presents a series of scenarios produced by WEM. The aims of the scenario analysis are to investigate the roles of energy production and global warming on future socioeconomic growth and evaluate the likelihood of industrial decline.

Global industrial output is reported for each scenario as it is the main driver of the socioeconomic systems in World3 and WEM. A fixed percentage of industrial output is allocated to society's consumption. The remaining output is invested into generating energy, improving efficiencies and building capital for the future production of food, services and industrial output. Industrial output is just a component of GDP. A GDP measure has not been explicitly modelled; defining a financial value to all aspects of global production was considered beyond the scope of this paper.

4.1 Scenario 0 - No Global Warming and Fixed Energy Costs

The first case to consider is a reference one whereby global warming is removed and the Fraction of Capital Allocated to Generating Energy (FCAGE) remains constant. The projected state of the world is presented in Figure 15.

Population growth slows, levels off at almost 10 billion, and then starts a gradual decline as increasing wealth leads to a reduction in birth rates. Industrial growth rates also slow slightly due to the increasing fraction of capital being diverted towards the agricultural sector to sufficiently increase yields. The Compounded Average

Annual Growth Rate (CAAGR) of industrial output from 2020-2100 is 1.8%, compared to 3.2% in the previous 80 years.

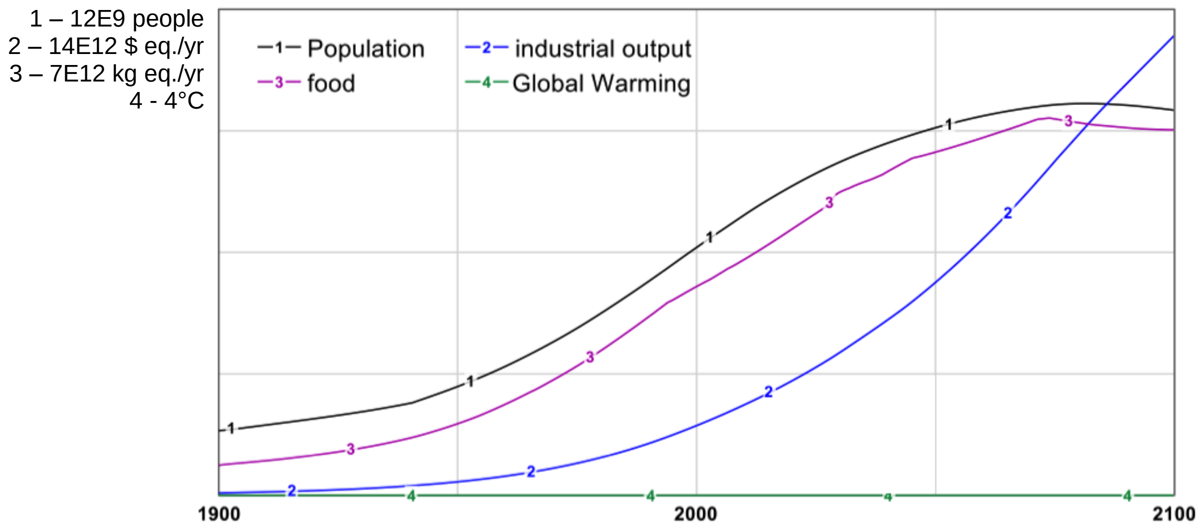

Figure 15; State of the World in Scenario 0 – Reference case whereby FCAGE remains constant and climate change is ignored

4.2 Scenario 2 - Current trends

Figure 16 presents the state of the world for scenario 2; the ‘standard run’ based on current energy trends. Increased energy costs and global warming shift capital away from industrial output; the CAAGR (2020-2100) of which is reduced from 1.8% in Scenario 0 to 1.3%. Industrial output per capita grows throughout the modelled timeline but the slower rate translates to a slower improvement in the material quality of life.

By 2100, 2.4°C of global warming is projected but significant GHG emissions are still being released; extrapolation suggests warming would reach 2.8°C in the subsequent decades. This is lower than most mainstream estimates due to the relatively low industrial growth rate (see Section 4.5).

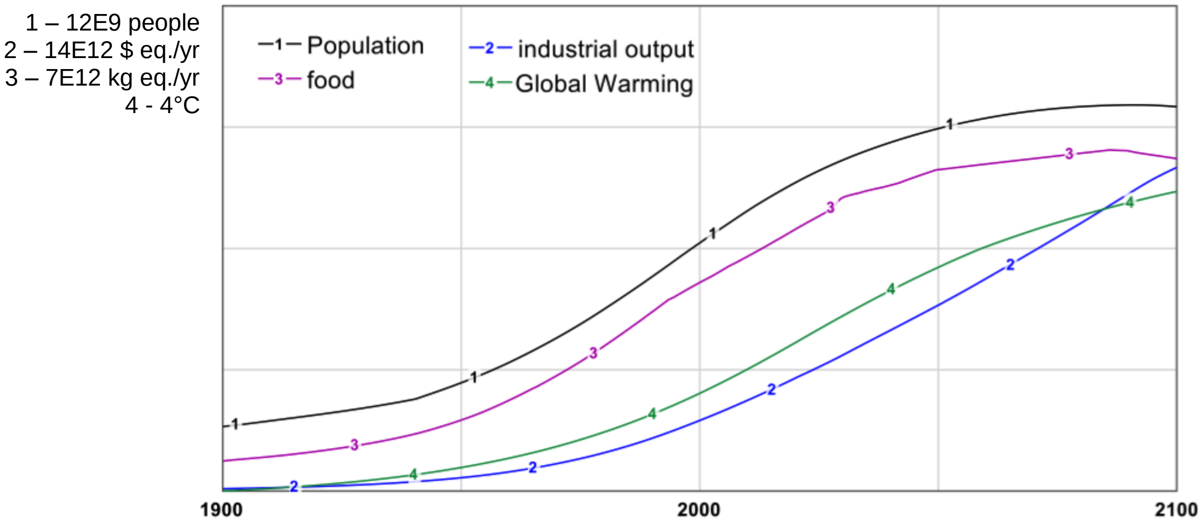

Figure 16; State of the World in Scenario 2 – Steady socioeconomic growth projected for the 'standard run' which is based on current energy trends

4.3 Comparison to World3

The state of the world projected by WEM in Figure 16 can be compared against the typical LTG scenario shown in Figure 2. There are relatively few differences between the two models but their outputs vary substantially; World3's baseline scenarios present global collapse and WEM projects stable growth.

Replacing various pollutants with GHG emissions narrows the scope of constraints being considered and so makes WEM more optimistic than World3. However, the driving factor behind the substantial change in results is the way that physical constraints have been modelled.

Figure 17 compares the behaviour of the resource cost in World3 (FCAOR) with the energy cost in WEM (FCAGE). There is a step increase in the FCAGE as the energy industry transfers from fossil fuels to more abundant renewable and nuclear technologies. The FCAOR increases far more dramatically and only levels off as it approaches 1; unsurprisingly, this drives industrial collapse.

The rapid growth of FCAOR may be applicable to the cost of a specific resource but it is not representative of the aggregated cost of obtaining resources. Different resources will reach a reserve crisis at different times. As the cost of one resource increases, more abundant substitutes will take its place. At some point in the future, reserves of such substitutes may become an issue and the process will be repeated. The expected dynamic would therefore be a series of step increases, like the behaviour of FCAGE.

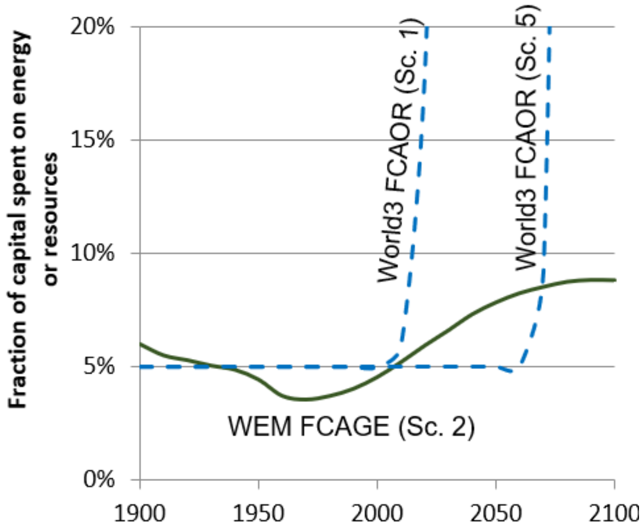

Figure 17; WEM vs World3 - The projected FCAGE is far less volatile than World3's FCAOR

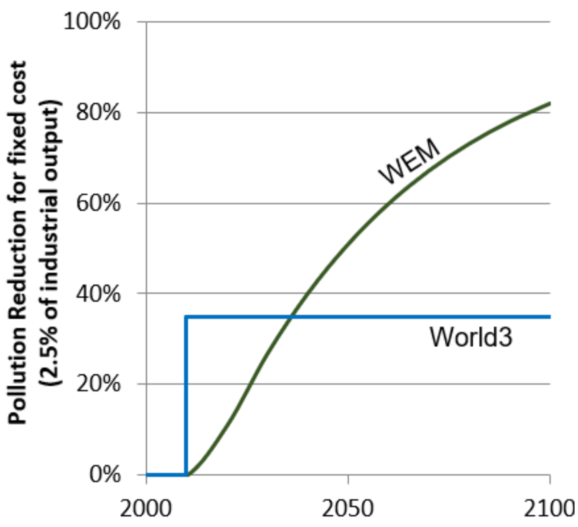

Figure 18; WEM vs World3 - Pollution reduced exponentially in WEM and by a fixed factor in World3

Pollution projections also differ substantially between the two models; agricultural yield reductions peak at about 90% in some World3 scenarios but only at 20% in WEM. Figure 18 compares the pollution reduction factor for a constant investment.

WEM assumes that a constant investment leads to an exponential decrease in pollution. There is a partial decoupling between the driver (energy consumption) and the pollutant (GHG emissions) due to technology improvements. In World3, exponential pollution control is included in some scenarios. However, the cost of this technology is a function of the pollution reduction factor and independent of time. An annual investment is required to hold pollution control at a constant level.

This comparison supports common critiques of the model that it underestimates the value of technology and fails to model the effect of sparse resources being replaced by more abundant ones. The difference between the models' results support the argument that the work of a single model cannot be used as the sole guide to public policy in such a complex area (Hayes 2012).

4.4 Climate Change Mitigation Sensitivity

Further scenarios in WEM investigate the impact of climate change policies on the future state of the world. Scenario 1 removes all attempts to reduce GHG emissions and Scenario 3 limits global warming to 2°C. The Future of Energy model (FEM) contains an explicit delay in transferring energy production towards the idealised mix. This makes it almost impossible to reduce global warming below 2°C. Scenario CCS overcomes this by retrofitting CCS to existing coal and gas plants. The cost of retrofitting existing plants is assumed to be 20% higher than building new CCS plants (McKinsey&Company 2008).

Figure 19 illustrates that if global society chooses to use more capital and labour on mitigating climate change, then the result is a reduction in the rate of growth in industrial output (and therefore consumption). By 2100, industrial output in scenario 3 (2°C target) is 13% lower than for scenario 1 (no pollution control) and the total value of services is 24% lower. Food production is largely unaffected by additional efforts to reduce GHG emissions; reduced investments in agricultural are cancelled out by reduced yield degradation from global warming.

The relationship is non-linear with industrial output growth rates decreasing faster as global warming is further reduced. The cheapest emission cuts are made first. Limiting warming to 1.5°C requires the rollout of new or expensive technologies and changes to sectors where low carbon options are very limited (IEA 2016b).

Ignoring GHG emission control maximises consumption but would lead to environmental and social stress in the short-term, and greater economical constraints for future centuries. Policies must ultimately define an acceptable sacrifice in material growth to limit the potentially irreversible damage of climate change.

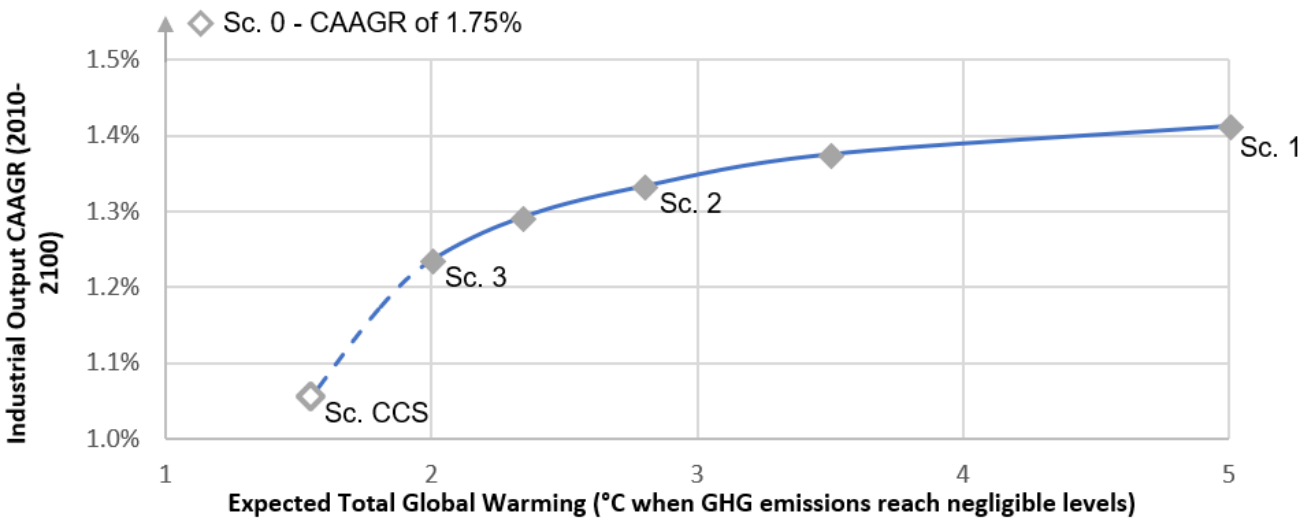

Figure 19; The rate of consumption growth declines when more capital is used to reduce GHG emissions

4.5 High Growth Scenarios

All the scenarios discussed thus far project far lower rates of economic growth than current mainstream economic estimates. A set of high growth scenarios were created by defining more favourable growth conditions within WEM. Table 2 compares the projections for the various pollution control scenarios.

Table 2; High Growth Scenario Analysis - Comparison of climate change and industrial output projections

	Global warming in 2100 / CAAGR of industrial output (2020-2100)				
	Scenario 0	**Sc. 1**	**Sc. 2**	**Sc. 3**	**Sc. CCS**
Original Scenarios	NA / 1.8%	3.1°C / 1.4%	2.4°C / 1.3%	1.9°C / 1.2%	1.5°C / 1.1%
High Growth Scenarios	NA / 2.5%	3.7°C / 2.0%	2.7°C / 1.9%	2.1°C / 1.7%	1.6°C / 1.6%

The detrimental effects of global warming and increasing energy production costs are greater for the high growth cases; the CAAGR of industrial output is reduced by 0.6-0.9% compared to 0.3-0.7% in the baseline scenarios. Consumption will not grow with the total economy, because as the economy gets bigger, a larger fraction of output has to be allocated to either reducing GHG emissions or dealing with the consequences of increased global warming.

Scenario 2 (expected trends) leads to 2.7°C of global warming by 2100, compared to 2.4°C in the baseline run. For comparison, the Climate Action Tracker also projects current policies and targets to drive warming of 2.7°C by 2100 (Climate Action Tracker 2015).

4.6 Breaking the World

A final set of scenarios have been generated to assess what needs to change for WEM to plot industrial decline. Projecting the world with a more pessimistic outlook helps to test the sensitivity of the results presented thus far.

WEM cannot be made to project industrial decline within the 21st century using the identified range of realistic assumptions. The timeline has therefore been extended to 2150. All the scenarios presented thus far remain stable over this period but increased global warming and continued material growth places greater pressure on the socioeconomic system. WEM is now making projections over a 130-year period, the same as the original World3 model.

Scenario 4 starts with Scenario 2 (current energy trends) and then investigates the potential for increased energy costs to cause global collapse. The projected cost of energy was increased by 80% from 2020 onwards. Figure 20 summarises WEM's projections. Industrial growth is slowed but a decline in material wealth is still avoided. Increasing energy costs further required making unrealistic changes to all major energy sources.

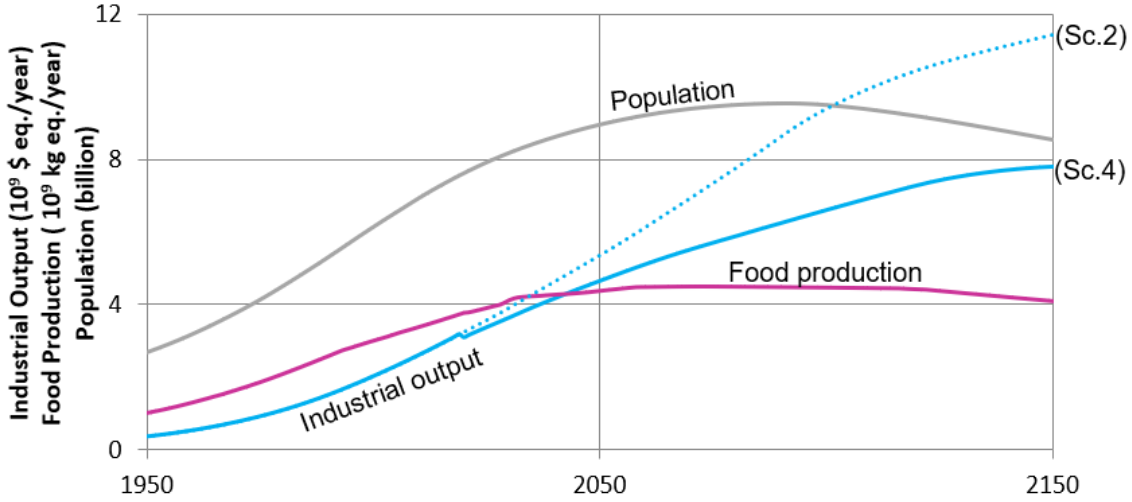

Figure 20; State of the World in Scenario 4 - Increased energy costs slow industrial growth, but are not sufficient to drive decline

Scenario 5 again starts with Scenario 2 and then tests whether climate change can drive industrial decline. Agricultural yield degradation has been increased from 8% to 15% at 3°C of warming. This follows the most pessimistic estimates presented in Figure 13 and represents excluded factors in studies (such as the increase in extreme weather patterns) cancelling out the effects of carbon fertilisation.

Secondly, warming is assumed to be more sensitive to GHG emissions than previously modelled, with an additional warming of 0.8°C after 2.5°C. This increase is well within climate sensitivity estimates; the IPCC quantified a range of 1.5°C - 4.5°C as "likely" for a doubling of CO_2 concentration (IPCC 2015). Scenario 5 is therefore considered pessimistic but plausible.

Figure 21 presents the state of the world; an 'agricultural crisis' driven by climate change. Global warming drives agricultural yields down faster than the population falls. As a result, increasing capital is diverted away from industry towards food production. Eventually, investment in industrial capital cannot match depreciation and so output starts to fall. By 2150, the system is set in a negative spiral and output would continue to fall if WEM was run further.

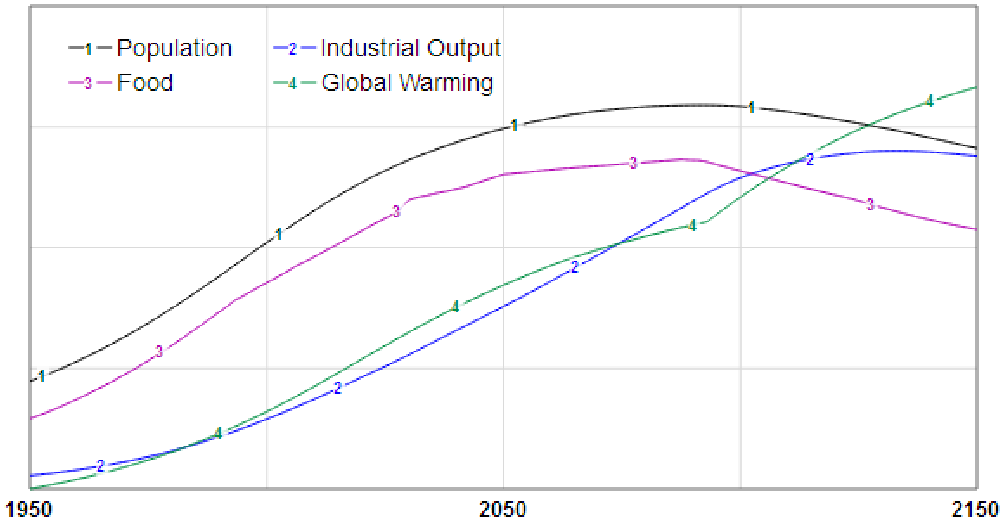

Figure 21; State of the World in Scenario 5, an 'Agricultural Crisis' - Pessimistic climate changes assumptions lead to significant degradation of agricultural yields and the onset of industrial decline

The scenarios presented thus far project that the global population will peak within the 21st century. This is consistent with the LTG thinking but conservative compared to mainstream estimates; WEM's population growth is equivalent to the low 20th percentile UN projection (UN 2017).

Scenario 6 investigates the role of population growth on the likelihood of industrial decline. WEM projects that an increase in population reduces total industrial output. A greater population demands more services and more food, diverting capital away from industry. There is no productivity benefit to having more people; WEM models industrial output as a function of capital rather than labour.

A sufficient increase in population growth creates the same 'agricultural crisis' as presented in Scenario 5. Figure 22 presents the minimum population and climate change conditions required to drive industrial decline; defined as a 1% fall from peak industrial output peak to the output in 2150. The results are more sensitive to population changes than GHG emission policies. Even where the effects of climate change are completely removed, the population growth required to drive industrial decline is far from unreasonable.

Greater population growth makes it harder to both improve the global material quality of life and sustain the environment. Many politicians are afraid to broach the topic even though the key policy recommendations are relatively simple; healthcare, education and voluntary access to family planning services should be made more available to poor communities in least-developed countries (Bryant et al. 2009).

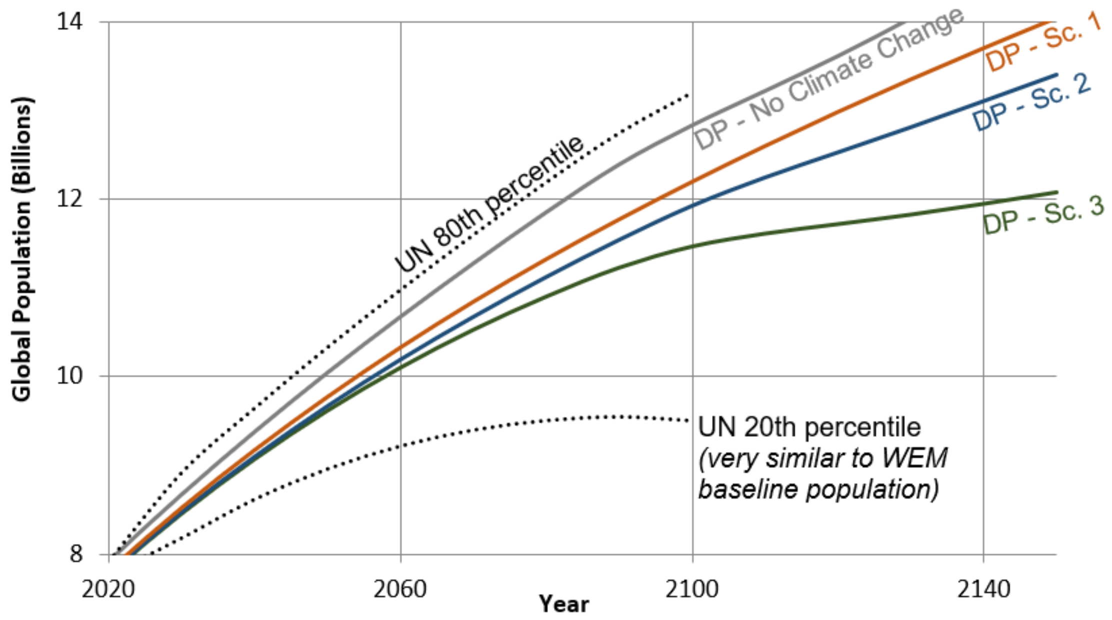

Figure 22; Population Growth and Industrial Decline - The Decline Population (DP) is the minimum growth required to drive industrial decline in WEM before 2150 and appears reasonable even when climate change effects are removed.

4.7 Future Work

There is enormous potential and scope for future work on both WEM and the original World3 model. The following opportunities could see WEM developed into a more useful tool:

- Re-evaluate the agricultural sub-sector (which drives industrial decline in Figure 22 but has not been reviewed in detail in this study) and assess the sensitivity of WEM's projections to agricultural changes.
- Incorporate a GDP measure. WEM projects that limiting global warming leads to lower consumption growth, but this does not necessarily mean a reduction in global GDP (which is boosted by the extra activities to reduce GHG emission).
- Research further impacts of climate change, such as changes to labour productivity.
- Investigate the effect of more specific energy policies. For example, WEM could project the global socioeconomic impacts of relying on future GHG emissions to be negative or of unlocking a new energy source such as nuclear fusion power.

5 Conclusion and Policy Implications

Analysis of energy source trends suggests that the cost of total energy production will increase over the next 80 years. This is predominantly due to rising oil costs and the lack of sufficient alternatives in the transport sector. The most significant end-point impacts of climate change have been defined as the financial cost from flooding and the decrease in agricultural yields.

WEM incorporates energy costs and global warming into a model of the global socioeconomic system. The scenarios produced by WEM suggest that:

Global collapse of the scale projected in the LTG is highly unlikely within the next century. The general behaviour mode of WEM is stable with industrial output growing throughout the 21st century for all the baseline scenarios. WEM includes more optimistic assumptions than World3 and models the impact of substitution in controlling energy costs.

Industrial decline is possible before 2150 if efforts to curb GHG emissions are insufficient and/or population growth is accelerated. This supports the LTG message that a managed decline in society's ecological footprint is necessary for economic sustainability. Industrial growth ends due to increasing capital being diverted into food production. Further research should evaluate the agricultural sub-sector and the sensitivity of WEM's projections to agricultural changes.

Investments in mitigating global warming lead to a reduction in the growth of industrial output (and therefore consumption) and services in the 21st century. This impact increases at tighter emission targets. Current policies are projected to lead to 2.4-2.7°C of global warming by 2100. Limiting global warming to 2°C reduces the CAAGR of industrial output (2020-2100) by 0.1-0.2%. However, the modelled timeline does not represent the full cost of unabated climate change; which some argue could eventually reach 5-20% of GDP (Stern 2007). Society must choose between the long-term benefits of limiting potentially irreversible climate change and a short-term cost to material wealth.

LTG used World3 as a warning against environmental overshoot and a basis for policy change. WEM's results are not so dramatic and will not be used to justify concrete policy recommendations. The shortcomings of the model must be recognised; the level of detail within WEM's sub-models is vastly inferior to specific energy or climate change models. Furthermore, the quantitative results from WEM are dependent on the relatively arbitrary assumptions made concerning future energy prices.

The key and relatively unique strengths of WEM are its global scope, extended timeline, and system dynamics methodology. The aim of WEM is to justify overarching trends and, at this stage, the model's results can only be used to recommend broad policy themes. However, future work could investigate the socioeconomic impacts of more specific energy policies or technology breakthroughs. This study supports the need for:

- A more global and long-term outlook in world politics.
- Greater recognition of the role of population growth on both material standards of living and environmental sustainability, and greater funding for education, healthcare and voluntary access to family planning services across less developed countries.
- Investments into alternative transport fuels to reduce the industry's reliance on oil

WEM is one of very few models that use the system dynamics approach to create an alternative set of projections to those given by World3. Developing explicit and examinable models can bring about a critical re-examination of our current mental models and stimulate further attempts to improve the process of model making (Meadows et al. 1973).

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7 Appendices

7.1 Appendix A - FEM Key Results

The projected cost and GHG emissions intensity of energy are presented in Table A.1**Error! Reference source not found.** and Table A.2. Scenarios 1.5 and 2.5 are intermediate scenarios whereby the pollution multiplier factors are half and double those of scenario 2 respectively.

Table A.1; FEM Results – The historic cost and GHG emissions intensity of energy production projected by FEM for all scenarios

Year	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Cost ($2016/toe)	266	243	234	223	215	195	163	156	163	178	201
GHG emissions (tonne CO2 eq./toe)	2.43	2.59	2.71	2.8	2.84	2.83	2.77	2.74	2.7	2.65	2.61

Table A.2; FEM Results – The projected cost and GHG emissions intensity of energy production to 2100

Year	Cost of Energy ($2016/toe)						GHG Emissions (tonne CO2 eq. / toe)					
	Sc1	Sc 1.5	Sc2	Sc 2.5	Sc3	Sc CCS	Sc1	Sc 1.5	Sc2	Sc 2.5	Sc3	Sc CCS
2010	230	231	231	231	231	231	2.62	2.59	2.56	2.56	2.56	2.57
2020	263	264	264	265	266	272	2.55	2.49	2.43	2.39	2.30	2.05
2030	292	294	295	296	299	309	2.48	2.38	2.30	2.21	2.06	1.53
2040	322	326	328	329	332	352	2.43	2.26	2.15	2.03	1.84	1.13
2050	343	349	352	354	357	386	2.38	2.16	2.01	1.87	1.66	0.82
2060	358	367	371	374	378	416	2.34	2.06	1.90	1.73	1.50	0.56
2070	368	378	384	388	393	435	2.30	1.98	1.79	1.61	1.36	0.48
2080	375	387	395	400	405	453	2.26	1.90	1.70	1.50	1.24	0.41
2090	376	390	399	405	411	470	2.23	1.83	1.61	1.40	1.13	0.32
2100	373	389	399	406	413	482	2.19	1.77	1.54	1.31	1.03	0.30

7.2 Appendix B - Recreating the World Energy Model (WEM)

World3-03, the model version from the latest LTG publication (Meadows et al. 2004), was provided by Dr Jorgen Randers for use in this study. This appendix gives sufficient detail to recreate WEM ***starting from World3-03.*** WEM was written in STELLA Architect version 1.2.2 (ISEE Systems 2017).

From World3-03:

- Delete the resource and pollution sub-models and all impacts they have on the model
- Import the energy and climate change sub-models given below and link outputs to the main model (notes 1-4)
- Edit original World3 variables in the agriculture and population sub-models (note 5)

1. Energy Sub-Model (Scenario 2)

Average_Cost_of_Energy = GRAPH(TIME)

(1900.0, 266.0), (1910.0, 243.0), (1920.0, 234.0), (1930.0, 223.0), (1940.0, 215.0), (1950.0, 195.0), (1960.0, 163.0), (1970.0, 156.0), (1980.0, 164.0), (1990.0, 178.0), (2000.0, 201.0), (2010.0, 231.0), (2020.0, 264.0), (2030.0, 295.0), (2040.0, 328.0), (2050.0, 352.0), (2060.0, 371.0), (2070.0, 384.0), (2080.0, 395.0), (2090.0, 399.0), (2100.0, 399.0)

Energy_Cost_Switch = 0

FCAGE = IF (TIME > Energy_Cost_Switch) THEN 0.00021*Average_Cost_of_Energy ELSE 0.05

2. Link between the Energy sub-model and original World3 variables

industrial_output_50 = industrial_capital_52*(1-**FCAGE**)*capacity_util_fr_83 / s_ind_cap_out_ratio_51

3. Climate Change Sub-Model (Scenario 2)

Cumulative_GHG_Emissions(t) = Cumulative_GHG_Emissions(t - dt) + (Emissions) * dt

INIT Cumulative_GHG_Emissions = 0

INFLOWS: Emissions = Annual_Emissions

Energy_Intensity(t) = Energy_Intensity(t - dt) + (- Eff_Improvement) * dt

INIT Energy_Intensity = 0.017

OUTFLOWS: Eff_Improvement = Energy_Intensity*Eff_Decrease

Annual_Emissions = Energy_Consumption*GHG_Emissions_Intensity/1000

CC_Switch = 0

Eff_Decrease = 1.631*fioa_Efficiency_1+0.0092

Eff_Invest_2 = 0.0066

Eff_Policy_Year = 2020

Energy_Consumption = Energy_Intensity*industrial_output_50/10^6

fioa_Efficiency = IF (TIME > CC_Switch) THEN fioa_Efficiency_1 ELSE 0

fioa_Efficiency_1 = IF (TIME > Eff_Policy_Year) THEN Eff_Invest_2 ELSE 0.0015

Flood_Cost = GRAPH(IF (TIME > CC_Switch) THEN Global_Warming ELSE 0)

(0.000, 0), (1.000, 0.001), (2.000, 0.003), (3.000, 0.005), (4.000, 0.009), (5.000, 0.014)

GHG_Emissions_Intensity = GRAPH(TIME)

(1900.0, 2.430), (1910.0, 2.590), (1920.0, 2.710), (1930.0, 2.800), (1940.0, 2.840), (1950.0, 2.830), (1960.0, 2.770), (1970.0, 2.740), (1980.0, 2.700), (1990.0, 2.650), (2000.0, 2.610), (2010.0, 2.560), (2020.0, 2.490), (2030.0, 2.410), (2040.0, 2.290), (2050.0, 2.190), (2060.0, 2.090), (2070.0, 2.010), (2080.0, 1.930), (2090.0, 1.850), (2100.0, 1.780)

Global_Warming = GRAPH(Cumulative_GHG_Emissions)

(0, 0.000), (1500, 1.000), (3000, 2.000), (4500, 2.900), (6000, 3.750), (7500, 4.600), (9000, 5.500)

industrial_output_50 = industrial_capital_52*(1-FCAGE)*capacity_util_fr_83/s_ind_cap_out_ratio_51

Land_Yield_Degradation_Factor = GRAPH(IF (TIME > CC_Switch) THEN Global_Warming ELSE 0) (0.000, 1.000), (1.000, 0.980), (2.000, 0.955), (3.000, 0.920), (4.000, 0.880), (5.000, 0.820)

4. Link between the climate change sub-model and original World3 variables

fioa_ind_56 = (1 - s_fioa_agr_93 - s_fioa_serv_63 - s_fioa_cons_57 - **fioa_Efficiency** - **Flood_Cost**)

land_yield_103 = s_land_yield_fact_104*land_fertility_121*land_yield_mlt_cap_102*s_yield_mlt_air_poll_105***Land_Yield_Degradation_Factor**

5. Changes to original World3 variables

soc_fam_size_norm_39 = GRAPH(del_ind_out_pc_40)

(0.0, 1.250), (200.0, 0.940), (400.0, 0.780), (600.0, 0.725), (800.0, 0.680)

land_yield_mlt_cap_102 = GRAPH(agr_inp_per_hect_101)

(0, 1.00), (40, 3.00), (80, 4.50), (120, 5.00), (160, 5.30), (200, 5.60), (240, 5.90), (280, 6.10), (320, 6.35), (360, 6.60), (400, 6.90), (440, 7.20), (480, 7.40), (520, 7.60), (560, 7.80), (600, 8.00), (640, 8.20), (680, 8.40), (720, 8.60), (760, 8.80), (800, 9.00), (840, 9.20), (880, 9.40), (920, 9.60), (960, 9.80), (1000, 10.00), (1040, 10.15), (1080, 10.30), (1120, 10.40), (1160, 10.50), (1200, 10.60), (1240, 10.70), (1280, 10.80), (1320, 10.90), (1360, 11.00), (1400, 11.10)

7.3 Appendix C - Recreating WEM's Scenarios

This appendix outlines how to recreate each of WEM's scenarios.

Scenario #2 – follow steps to recreate the model given in Appendix B.

Scenario #0 - start with scenario #2 and switch off the impacts of increasing energy and climate change constraints:

Energy_Cost_Switch = 4000

CC_Switch = 4000

Scenario #1, #1.5, #2.5, #3 and Scenario CCS - start with scenario #2 and vary the cost of energy, GHG emissions intensity and efficiency investment:

Average_Cost_of_Energy = scenario values in Table A.2

GHG_Emissions_Intensity = scenario values in Table A.2

Eff_Invest_2 = scenario values in Table A.3**Error! Reference source not found.**

Table A.3; WEM Inputs - Efficiency investment (% of Industrial Output) from 2020 to 2100 by scenario

Sc. 1	Sc. 1.5	Sc. 2	Sc. 2.5	Sc. 3	Sc. CCS
0%	0.4%	0.66%	0.9%	1.2%	1.8%

Scenario H#0, H#1, H#2 and **H#3 -** start with respective numbered scenario (ie. scenario #2 for H#2) and reduce agricultural constraints:

s_fioa_agr_93 = IF (TIME > 2017) THEN p_fr_io_al_agr_2_95*0.8 ELSE p_fr_io_al_agr_2_95

Scenario #4 - start with scenario #2 and test pessimistic energy cost assumptions:

Cost_multiplier = IF(TIME<2020) THEN 1 ELSE 1.8

FCAGE = IF (TIME > Energy_Cost_Switch) THEN 0.00021*Average_Cost_of_Energy***Cost_multiplier** ELSE 0.05

Scenario #5 - start with scenario #2 and add pessimistic climate change assumptions:

Land_Yield_Degradation_Factor = GRAPH(IF (TIME > CC_Switch) THEN Global_Warming ELSE 0) (0.000, 1.000), (1.000, 0.970), (2.000, 0.930), (3.000, 0.870), (4.000, 0.800), (5.000, 0.700)

Global_Warming = GRAPH(Cumulative_GHG_Emissions) (0, 0.000), (500, 0.333), (1000, 0.667), (1500, 1.000), (2000, 1.333), (2500, 1.667), (3000, 2.000), (3500, 2.300), (4000, 3.400), (4500, 3.900)

Scenario #6 - start with either scenario #1, #2 or #3 and increase population growth rates:

soc_fam_size_norm_39 = GRAPH(del_ind_out_pc_40)

Sc.1 - (0.0, 1.250), (200.0, 0.940), (400.0, 0.870), (600.0, 0.820), (800.0, 0.800)

Sc.2 - (0.0, 1.250), (200.0, 0.940), (400.0, 0.880), (600.0, 0.860), (800.0, 0.840)

Sc.3 - (0.0, 1.250), (200.0, 0.940), (400.0, 0.900), (600.0, 0.870), (800.0, 0.850)

TABLES

Table 1; Pollution Factors - Energy source pollution factors are based on GHG emissions intensities from averaged datasets (EPA 2014; UK Gov 2016; IPCC 2014)

	Biofuel	Coal	Coal +CCS	Oil	Gas	Gas + CCS	Nuclear	Renewables
GHG emissions (Coal=100)	27	100	15	79	57	9	1	3
Pollution Costs factor	27	120	35	79	57	9	100	3

Table 2; High Growth Scenario Analysis - Comparison of climate change and industrial output projections

	Global warming in 2100 / CAAGR of industrial output (2020-2100)				
	Scenario 0	**Sc. 1**	**Sc. 2**	**Sc. 3**	**Sc. CCS**
Original Scenarios	NA / 1.8%	3.1°C / 1.4%	2.4°C / 1.3%	1.9°C / 1.2%	1.5°C / 1.1%
High Growth Scenarios	NA / 2.5%	3.7°C / 2.0%	2.7°C / 1.9%	2.1°C / 1.7%	1.6°C / 1.6%

Table A.1; FEM Results – The historic cost and GHG emissions intensity of energy production projected by FEM for all scenarios

Year	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Cost ($2016/toe)	266	243	234	223	215	195	163	156	163	178	201
GHG emissions (tonne CO2 eq./toe)	2.43	2.59	2.71	2.8	2.84	2.83	2.77	2.74	2.7	2.65	2.61

Table A.2; FEM Results – The projected cost and GHG emissions intensity of energy production to 2100

Year	Cost of Energy ($2016/toe)						GHG Emissions (tonne CO2 eq. / toe)					
	Sc1	Sc 1.5	Sc2	Sc 2.5	Sc3	Sc CCS	Sc1	Sc 1.5	Sc2	Sc 2.5	Sc3	Sc CCS
2010	230	231	231	231	231	231	2.62	2.59	2.56	2.56	2.56	2.57
2020	263	264	264	265	266	272	2.55	2.49	2.43	2.39	2.30	2.05
2030	292	294	295	296	299	309	2.48	2.38	2.30	2.21	2.06	1.53
2040	322	326	328	329	332	352	2.43	2.26	2.15	2.03	1.84	1.13
2050	343	349	352	354	357	386	2.38	2.16	2.01	1.87	1.66	0.82
2060	358	367	371	374	378	416	2.34	2.06	1.90	1.73	1.50	0.56

2070	368	378	384	388	393	435	2.30	1.98	1.79	1.61	1.36	0.48
2080	375	387	395	400	405	453	2.26	1.90	1.70	1.50	1.24	0.41
2090	376	390	399	405	411	470	2.23	1.83	1.61	1.40	1.13	0.32
2100	373	389	399	406	413	482	2.19	1.77	1.54	1.31	1.03	0.30

Table A.3; WEM Inputs - Efficiency investment (% of Industrial Output) from 2020 to 2100 by scenario

Sc. 1	Sc. 1.5	Sc. 2	Sc. 2.5	Sc. 3	Sc. CCS
0%	0.4%	0.66%	0.9%	1.2%	1.8%

Figure(s)

FIGURES

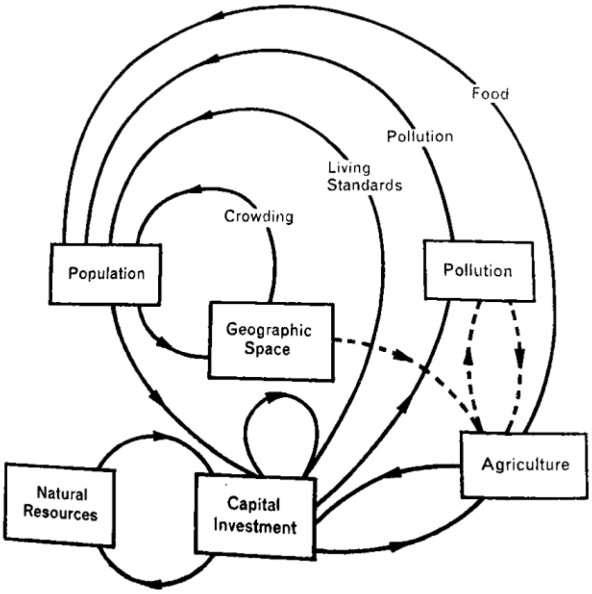

Figure 1; World3's Main Feedback Loops - The boxes represent the main subsystems and the arrows show the causal links (Cole et al. 1973)

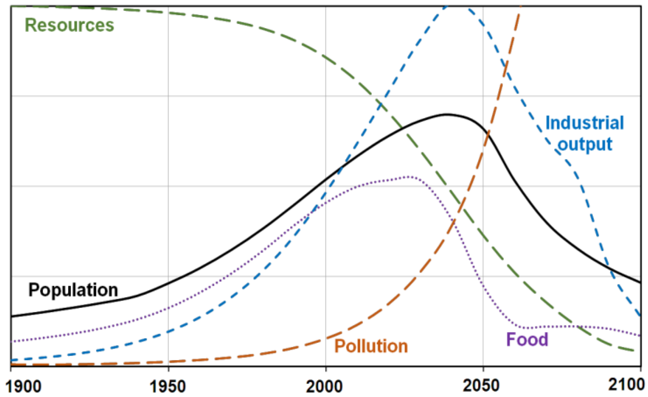

Figure 2; World3-03 Scenario 2 – Global industrial collapse is projected due to increasing resource and pollution costs (Meadows et al. 2004)

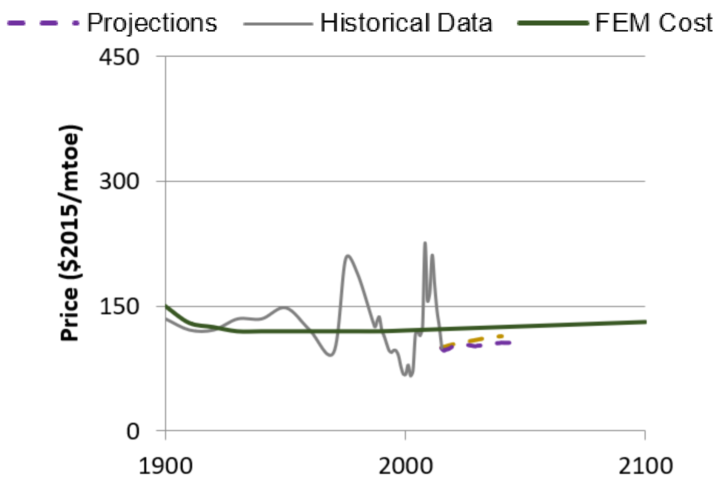

Figure 3; Coal Prices - Approximate historical data from 1900 (McNerney et al. 2011)*, detailed from 1987* (BP 2016) *and projections to 2050* (IEA 2016b; EIA 2017)

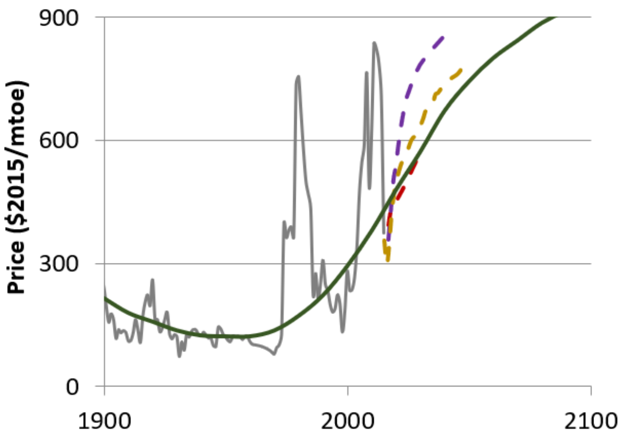

Figure 4; Oil Prices - Historical data from 1860 (BP 2016) *and projections to 2050* (The World Bank 2017; IEA 2016b; EIA 2017)

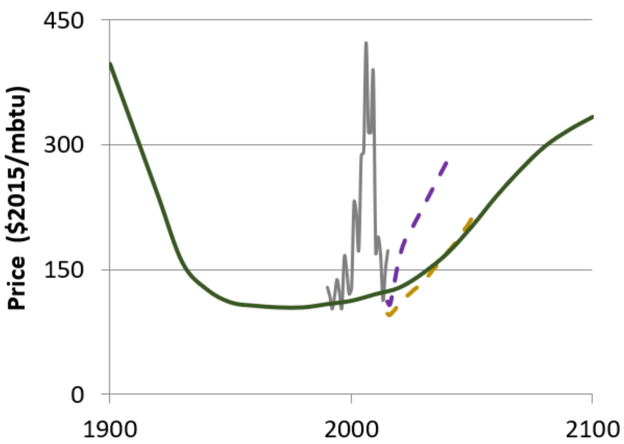

Figure 5; Natural Gas Prices - Historical data from 1989 (BP 2016) *and projections to 2050* (EIA 2017; IEA 2016b)

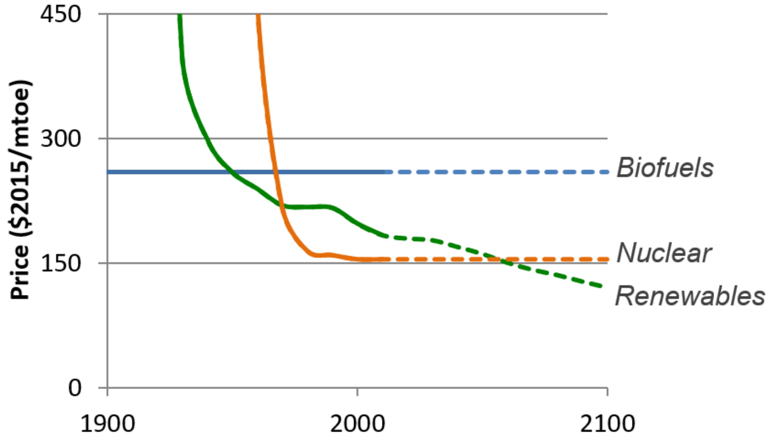

Figure 6; Biofuel, Renewable and Nuclear Prices - Estimates from secondary data and exclude demand cost factors for nuclear & renewables

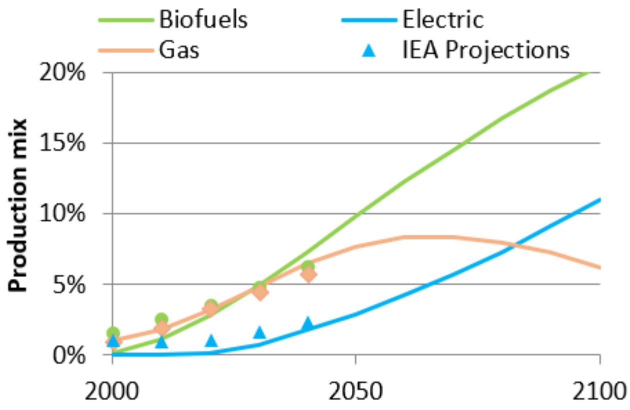

Figure 7; Alternative Fuels Transport Production Mix- FEM projections against target IEA projections

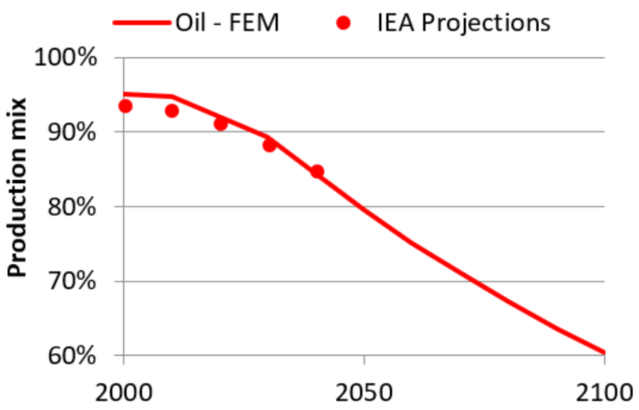

Figure 8; Oil Transport Production - FEM projections against target IEA projections

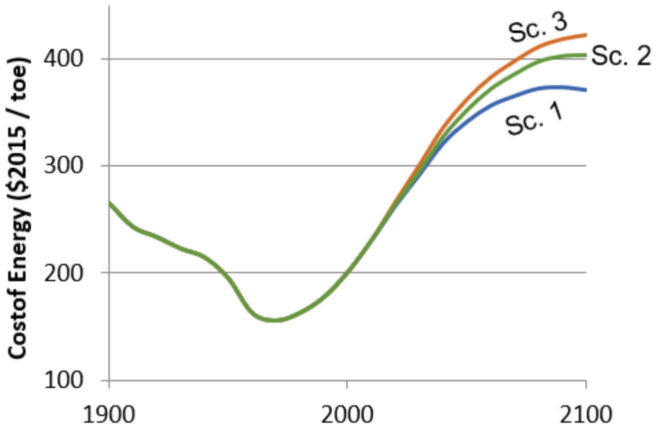

Figure 9; FEM Energy Cost Projections

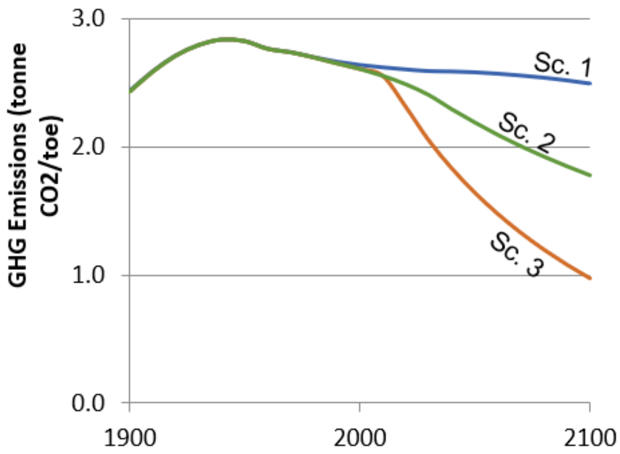

Figure 10; FEM GHG Emission Intensity Projections

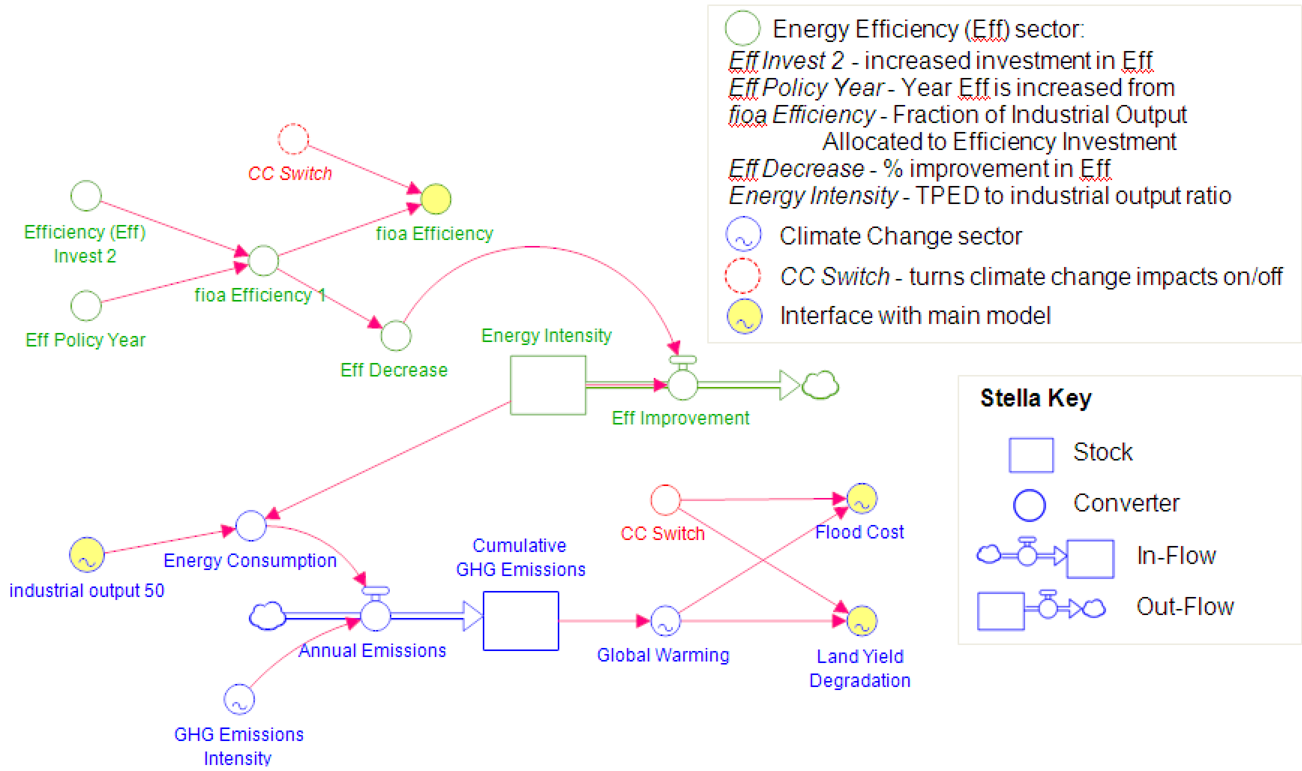

Figure 11; WEM Climate Change Sub-model – System dynamics model to calculate the end-point impacts of climate change

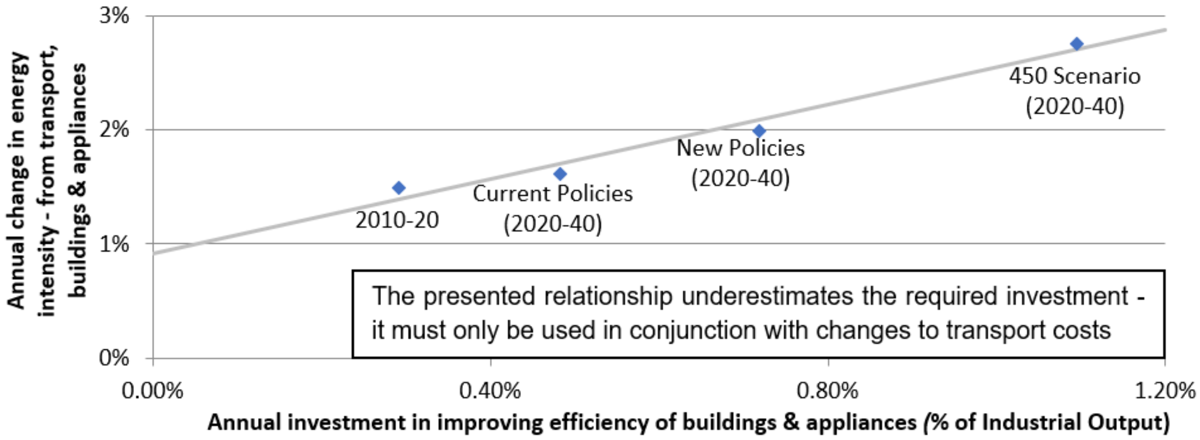

Figure 12; WEM Energy Intensity - Reduction of energy intensity proportional to the efficiency investment - data points based on IEA scenario analysis (IEA 2016b)

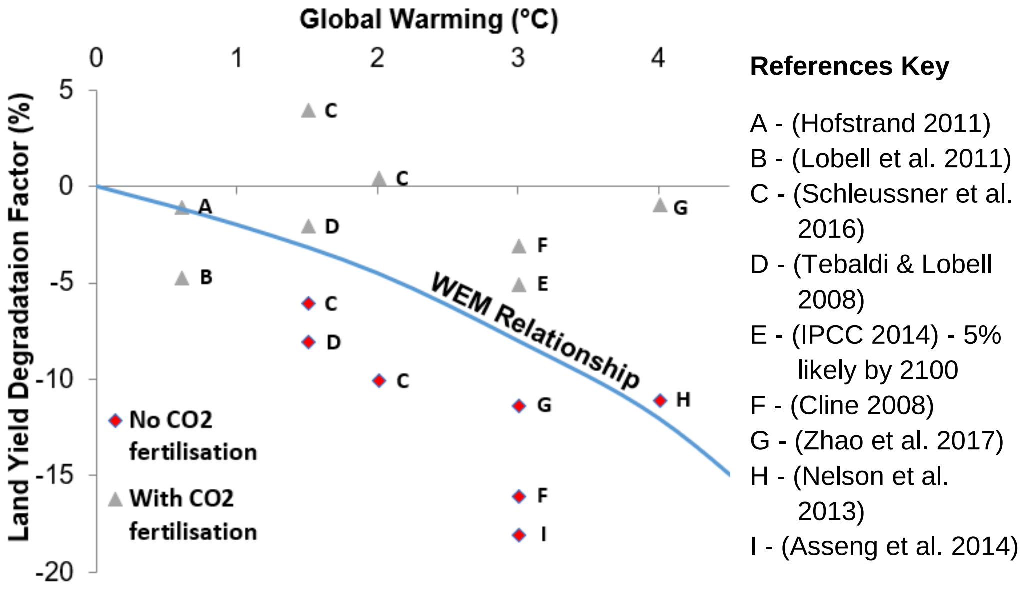

Figure 13; Agricultural Yield Degradation - The assumed relationship between global warming and globally aggregated crop yields takes account of estimates both with and without carbon dioxide fertilisation

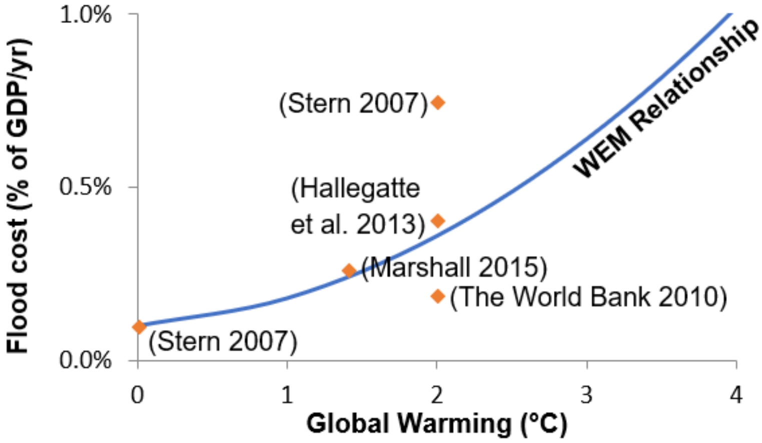

Figure 14; Flood Costs - Global warming drives a non-linear increase in 21st century flood damage costs

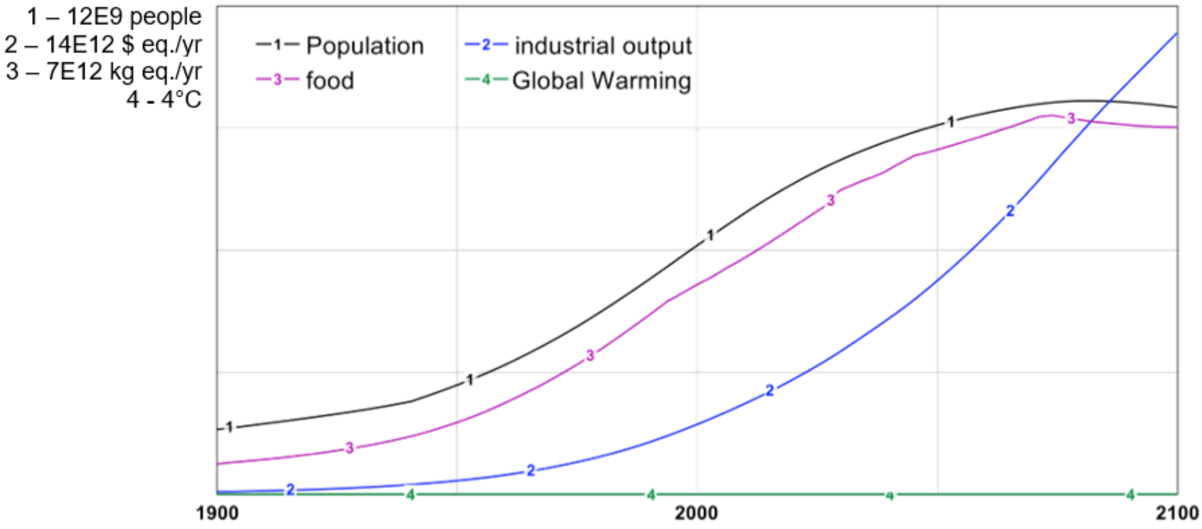

Figure 15; State of the World in Scenario 0 – Reference case whereby FCAGE remains constant and climate change is ignored

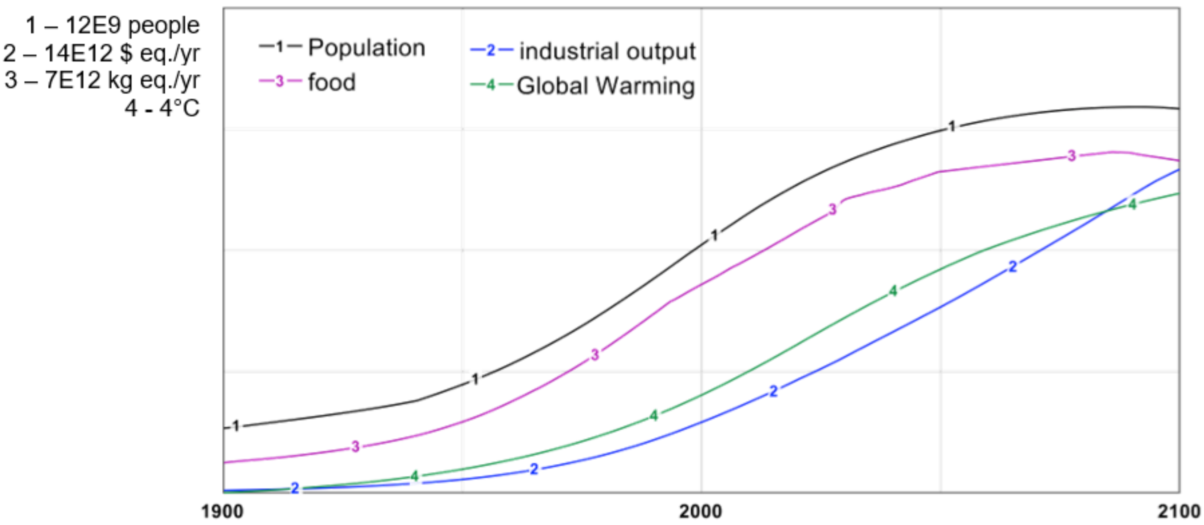

Figure 16; State of the World in Scenario 2 – Steady socioeconomic growth projected for the 'standard run' which is based on current energy trends

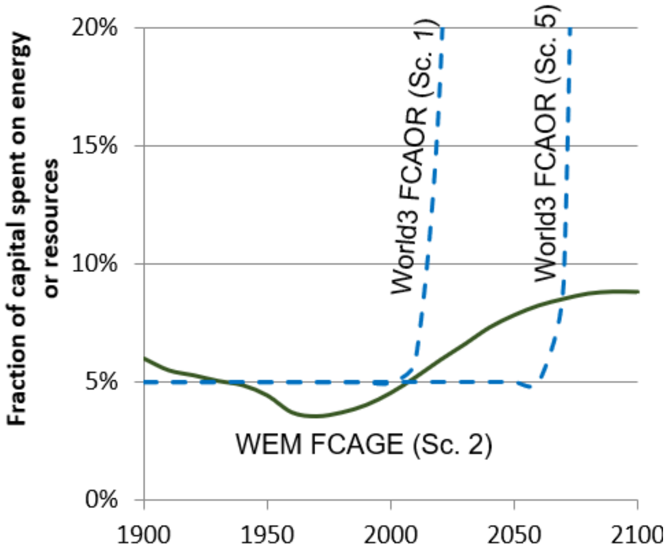

Figure 17; WEM vs World3 - The projected FCAGE is far less volatile than World3's FCAOR

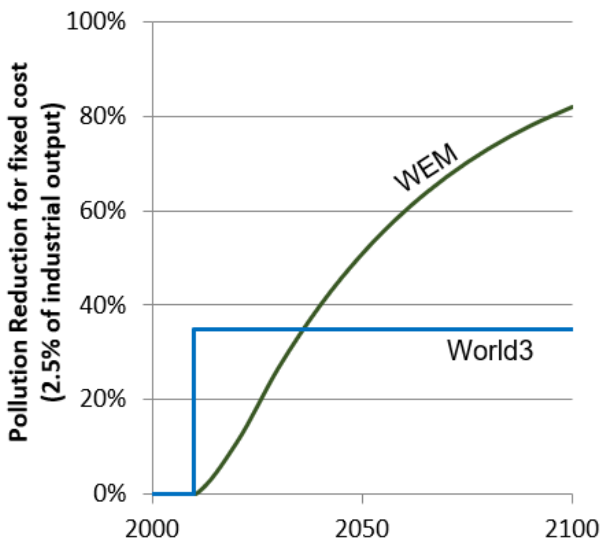

Figure 18; WEM vs World3 - Pollution reduced exponentially in WEM and by a fixed factor in World3

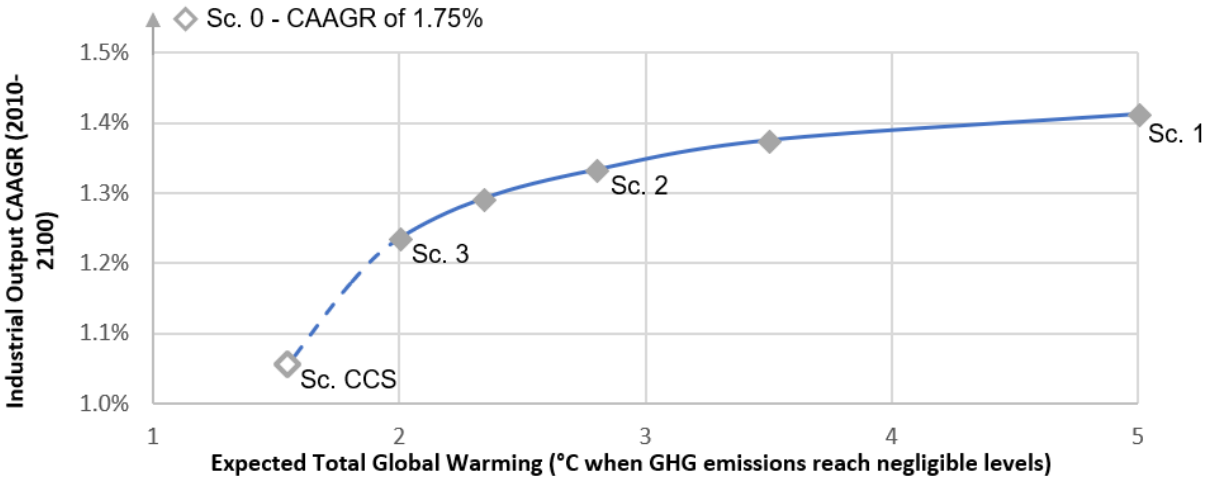

Figure 19; The rate of consumption growth declines when more capital is used to reduce GHG emissions

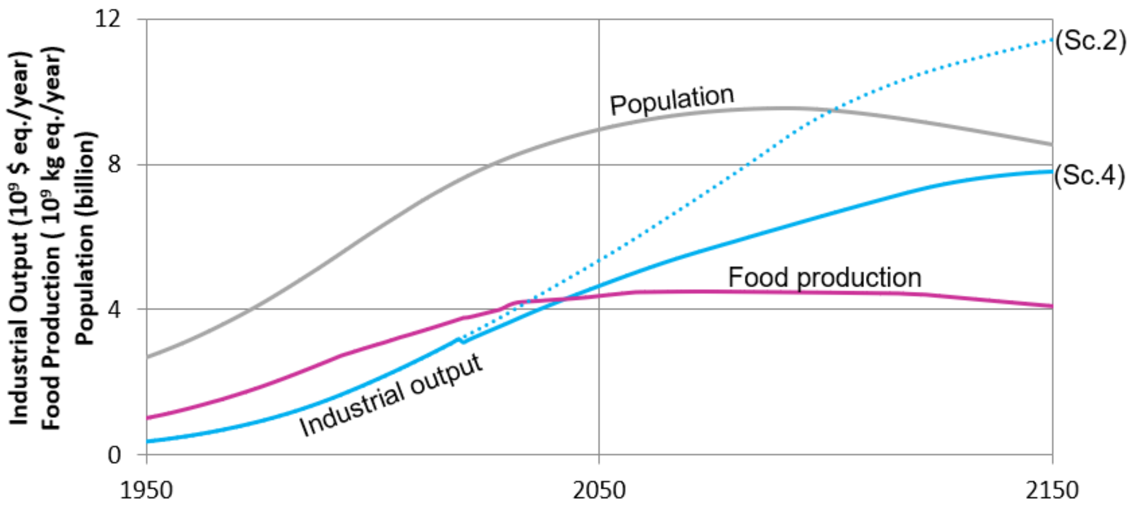

Figure 20; State of the World in Scenario 4 - Increased energy costs slow industrial growth, but are not sufficient to drive decline

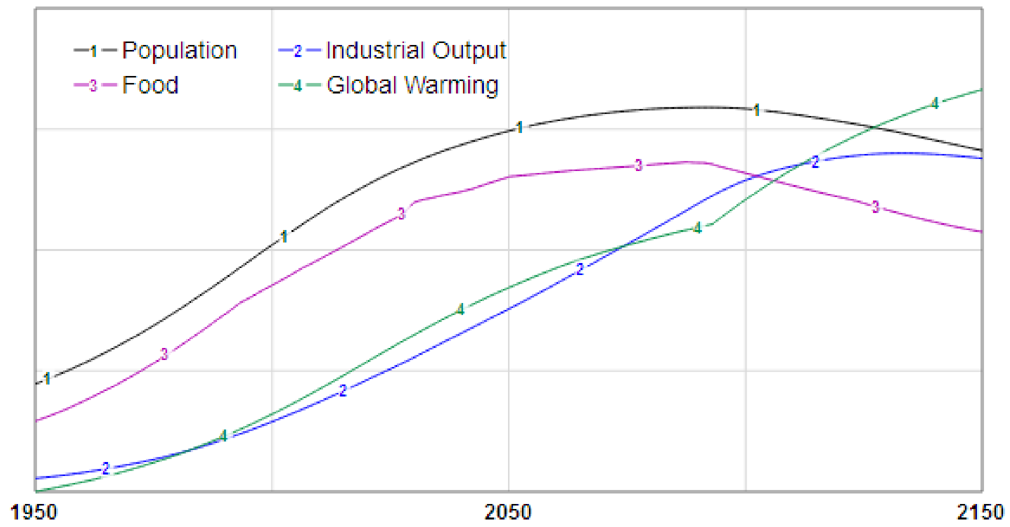

Figure 21; State of the World in Scenario 5, an 'Agricultural Crisis' - Pessimistic climate changes assumptions lead to significant degradation of agricultural yields and the onset of industrial decline

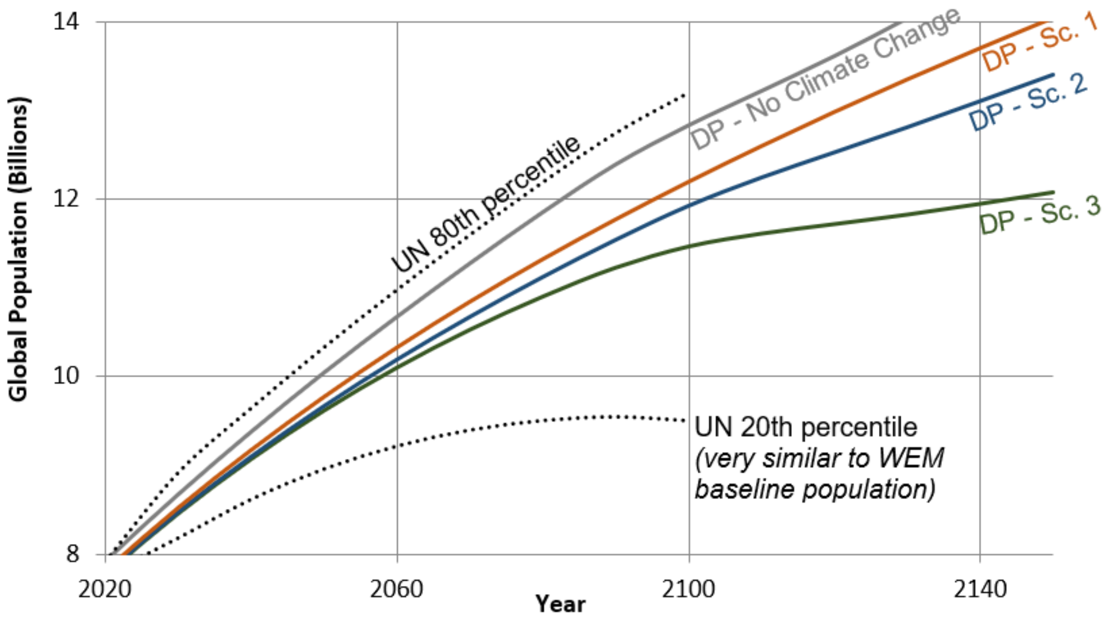

Figure 22; Population Growth and Industrial Decline - The Decline Population (DP) is the minimum growth required to drive industrial decline in WEM before 2150 and appears reasonable even when climate change effects are removed.